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AMONG the papers to appear in early issues of the *Journal* are the following:

"Arroyo-cutting and Filling." By ERNST ANTEVS

"Fabric of Quartzites near Thrust Faults." By ROBERT BALK

"Selenomorphology." By ALICE COLEMAN

"The Stability Relations of Anorthite and Its Hexagonal Polymorph in the System $CaAl_2Si_2O_8$-H_2O." By JULIAN R. GOLDSMITH and ERNEST G. EHLERS

"Replacement and Rheomorphic Dikes." By G. E. GOODSPEED

"Pleistocene Drift Sheets in the Lethbridge Region, Alberta, Canada." By LELAND HORBERG

"Origin of the Mima Mounds, Thurston County Region, Washington." By R. C. NEWCOMB

"Chemical Bonds and Distribution of Cations in Silicates." By HANS RAMBERG

"Pleistocene Evolution of the Ohio and Wabash Valleys." By WILLIAM J. WAYNE

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SMITH, A. V. (1926) Discovery of fish remains in Ordovician rocks of the Black Hills (abstr.): Geol. Soc. America Bull. 52, p. 27.

——— and DUNSANY, A. J. (1929*a*) Early Ordovician faunas of South Dakota: U.S. Geol. Survey Bull. 444, pp. 1–76.

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THE JOURNAL OF GEOLOGY

May 1952

THE FINER-GRAINED CALCALKALINE GRANITES OF NEW ENGLAND[1]

F. CHAYES

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ABSTRACT

Modal analyses for a collection of 145 thin sections of New England calcalkaline granites are presented and discussed. The data are used to estimate a range in which average or bulk modal compositions may be expected to fall. The internal variability of such granites is also examined in some detail. Remarkable internal homogeneity, rather small differences between granite masses, and consistent relation of data points for each mass to the thermal valley in the system Q-Or-Ab all suggest the existence of granitic (liquid) magmas as parent-materials. The origin of these magmas is not known; the most likely processes appear to be selective refusion and crystal fractionation. Critical evidence permitting a choice between these alternatives is not available, and it is curious that the difficulties confronting them are nearly identical.

DEVELOPMENT OF THE PROJECT

The first steps of any exploratory program are always carefully planned, but one usually hits pay dirt at some unpredictable—or unpredicted—site, and, if time and manpower are limited, the sensible thing is to follow the ore. The history of the present project is no exception.

At its start, in 1947, it was my general objective to supplement the admirable qualitative petrographic descriptions of granite with abundant quantitative modal data. It seemed best to rely on the tried and accepted technique of thin-section analysis rather than risk possible involvement in time-consuming complications which might arise in fragment analysis. Thus it was necessary to restrict the work to medium- and fine-grained granites in order to insure a maximum amount of information, for it is obvious that the area of a single thin section is an inadequate sample of a coarse-grained rock.

That useful results could be expected in this field from any but the most detailed study seemed most unlikely, and the first outline of the program called for a gradual advance from minor to major sources of variation. The initial step was re-examination of the precision or reproducibility of thin-section analysis. A by-product of this work was the development of a simple integrating device which has several advantages over earlier models (Chayes, 1949). The next step was to be a test of the variability of thin sections cut from a single hand specimen. This done, the volume (or area) of rock represented by the thin sections was to be gradually expanded, first, perhaps, to a small working face in a quarry, then to an entire quarry, then to a cluster of

[1] Manuscript received April 2, 1951.

quarries, and, finally, to an entire granite mass.

The immediate field problem, therefore, was location of a suitable quarry, and this proved no easy task. In the course of searching, I examined numerous quarries in several of the major commercial granite bodies in New England. During the first summer it happened that most of the quarries visited were rather small. From each, largely for reference purposes, a single hand specimen was collected. From each specimen a section was cut, and analyses of these sections soon placed the whole problem in a new light. In each case variation among thin sections from a given quarrying district was so small as to indicate that more detailed sampling was likely to prove unprofitable so long as the work was confined to granites of finer grain; more specifically, to those described by Dale (1907, 1908, 1923) as other than coarse or medium coarse.

The second step of the original outline —examination of within-specimen variability—was finally carried through on a reduced scale, with collections made at Westerly and Bradford, Rhode Island. The work was undertaken and published (Chayes, 1950*b*) only by way of placating and perhaps persuading skeptics, however; for information already on hand indicated that total variation in many granite bodies is but slightly greater than analytical error, even where only a single thin section per hand specimen is available.

The third step, really a series of steps involving gradual expansion of the volume of rock thought to be "represented" by the thin sections, so far has not been completed. I finally found a few quarries well suited to this type of work, and from one of them took a rather detailed sample. The thirty-five specimens in this sample, representing some 350 square feet of exposure in the Oak Hill Quarry, Swanville, Maine, have never been sectioned. Because of the volume of work involved and the cost of thin sections, it had been necessary to hold to a rather strict schedule. Before these particular specimens were reached, the focus of the whole program had changed. What had begun as a search for one particular quarry was continued as a sampling of as many quarries as I could find. The quarries had been important originally only because I thought they would yield large and easily accessible exposures of fresh rock. They now took on a new role as a convenient device for spreading the sample in each mass. From small quarries I continued to take only a single specimen, but in larger quarries I took a sample at each derrick site, where these could still be identified, or used other devices to avoid suppressing variation by too close spacing of specimens. The work in New England was continued until most of the better-known quarrying areas had been visited, and collections were made in all the major commercial bodies of medium grain or finer. In 1949 a similar quarry sampling of the pre-Cambrian granites of the Llano-Burnet area of central Texas was undertaken, and in 1950 the work was extended to the southeastern states. One may as well publish the results of such a program as they become available, for by its nature it must always be incomplete. Even the information about New England is fragmentary, and the strongest reason for presenting it here is the hope that it may stimulate other workers. I hope that even—and perhaps particularly—those who object most strongly to the findings will feel inclined to supplement their objections with numerous quantitative modes of specimens collected in the same

or a different fashion, from the same or different granite bodies. Only by persistent and conscientious work of this type can we escape from the embarrassing dilemma which finds one of the most obvious and fundamental properties of granite—its composition—playing at most a minor role in many theories concerning its origin.

METHOD AND GEOGRAPHICAL DISTRIBUTION OF SAMPLING

The material comprising the sample is perhaps best characterized as run-of-quarry product. In the smaller quarries, from which only one specimen was taken, large blocks were usually broken open, for this is always a quick way to obtain fresh material. In large quarries or where more than one specimen was taken, the specimens were usually broken out of the working faces. Sometimes this was not possible or practical, and in such cases grout blocks were again used. But every precaution was taken to insure that the samples were widely spaced. This could generally be accomplished by using irregular blocks found actually in the hole. Often the site from which such a block has been broken can be located without difficulty, and, in any case, New England practice was such that loose blocks lying in the working hardly would have been moved very far.[2]

In the few working quarries, samples were taken of material brought to the surface by each operating derrick. In most of the New England quarries operating at that time, derrick booms were rather short and did not overlap, and, except for samples of different facies—e.g., color, as at Westerly, or color index, as at Barre—no two of the specimens described in this report were separated by distances of less than 50 feet.

Originally it was intended that the number of specimens from each area should be proportional to the amount of granite, and in a very crude way I believe this to be so. But the correspondence is so crude as not to be very helpful, and in retrospect it seems that more would have been accomplished by setting a minimum sample size for each area, even if this had led to multiple sampling of rather small exposures, as it no doubt would, for instance, at Fernald Neck and Bethel. In the light of the results, it is clear that in most cases the variation of specimens taken at intervals of a mile or more will not be greatly different from that shown by specimens taken at 10- or even 1-foot intervals. This could hardly have been foretold, however, and from the current journal literature on the subject it certainly would not have been anticipated. It seemed logical, therefore, to take every precaution against suppressing variability by a too close spacing of specimens. The unfortunate result is that most of the theoretical discussion is forced to rely on areas represented by larger numbers of specimens; the smaller subsamples contribute very little to the argument.

By the end of two summers' field work the collection numbered well over three hundred specimens and included material drawn from nearly all the important commercial granites of New England. But by this time I had collected from most of the better-known coarse-grained localities and had done considerable rather detailed sampling in some of the finer ones. Excluding material falling in

[2] This would not be the case by any means in the Southwest, where grout was in many cases allowed to accumulate in the workings and consequently had to be moved around the quarry floor during operations. It would also not hold in the Southeast, where old holes are frequently used for grout storage from new workings. In New England, however, it was almost the universal practice to remove all quarried rock from the hole and store the grout as far as possible from the workings.

both of these categories, the sample conforming to the specifications already described—one specimen for each small quarry and a specimen per derrick (or equivalent) from larger quarries, none of the rocks to be coarser than medium-grained—amounted to 146 specimens, distributed as shown in table 1. From

TABLE 1

DISTRIBUTION OF HAND SPECIMENS

State	Area	No. of Specimens
Rhode Island	Westerly	13
	Bradford	5
Massachusetts	Westwood	8
	Chelmsford	2
New Hampshire	Concord	7
	Milford	13
	Fitzwilliam	14
Vermont	Bethel	1
	Barre	22
	Woodbury	8
Maine	North Jay	3
	Hallowell	5
	Pownal	14
	Fernald Neck	1
	Swanville	4
	Waldoboro	2
	Clark Island–Thomaston	12
	Vinalhaven	2
	North Sullivan	10
Total		146

each of the hand specimens a single thin section was cut, stained, and analyzed (detailed results are given in table 19).

No stranger to the region could have obtained satisfactory material in such a short time without constant reliance on Dale's (1907, 1908, 1923) splendid descriptions of the New England granites. Dale's studies were made when the industry was reaching its peak; in most areas there has been little subsequent development, and, wherever this is so, his work is still an invaluable and usually flawless field guide.

The maximum distance between any two of the quarry districts shown in the index map of the localities (fig. 1) is 280 miles (Westerly, Rhode Island, to North Sullivan, Maine), and all lie within a roughly triangular-shaped area of some 20,000 square miles, outlined by Westerly, Rhode Island, Woodbury, Vermont, and North Sullivan, Maine. Most of them lie along the north-south leg or the northeasterly-trending arcuate "hypotenuse" of this triangle. Very few are in the central portion of the area or along its northern margin. All the major and most of the minor commercial bodies of this type are included. Certain minor districts have been omitted, as well as a host of individual quarries scattered throughout New England. Many carefully studied granite masses of great geologic interest are not included simply because they have not been quarried; for some of these, modal analyses are already available or will eventually be generated as a by-product of detailed areal studies by other workers. If a particular granite mass had been extensively quarried, I usually sampled it even though others had already done so.[3] Quinn's well-known work on Bradford (1943) was published before my study was even planned, and many modes for the granites in the vicinity of Fitzwilliam were recently published by Mrs. Fowler-Billings (1949). Barre has been extensively studied in recent years, though little quantitative information about its com-

[3] Chelmsford is an exception. It was necessary to choose between a second trip to Maine and a more adequate sampling of Chelmsford and Ayer. Most of the Maine granites have never been adequately described. The Chelmsford and Ayer country, on the other hand, has been thoroughly studied in recent years, and publication of the full results is apparently only a question of time. It seemed more useful, therefore, to expand the Maine collection.

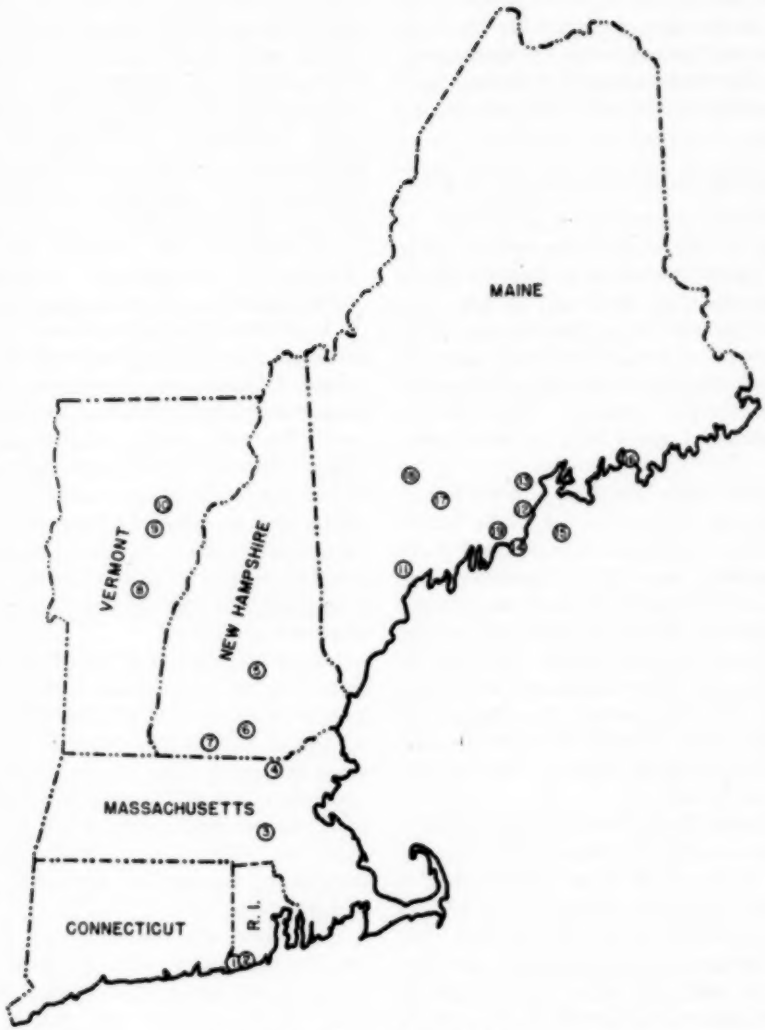


FIG. 1.—Index map of sample localities

position has been published. These and other cases in which results of more than one worker are available for the same mass are discussed in a succeeding section. For reasons described there, I finally decided to rely exclusively on my own data.

GENERAL MINERALOGY OF THE SAMPLE

Before examining the analytical results, it will be useful to review briefly the major mineralogical features of the rocks involved. Although no mass was either sampled or omitted because of the nature of its dark minerals, it turns out that all the rocks of the collection are biotite-muscovite granite. Muscovite is sometimes present only in small quantity.

Hornblende not clearly derived from enclosures occurs only at Clark Island, and even in this case it is confined to the immediate vicinity of gabbro-granite contacts. Pyroxene is never an essential constituent of any of these rocks and is almost everywhere absent. The only exceptions are Clark Island and Westwood, and even here, where the granites are closely involved with gabbro, they do not contain pyroxene except in obvious gabbro enclosures.

Commonly the rocks contain considerably more biotite than muscovite, and only in one of the larger suites, Concord, is this situation reversed. The average biotite content is usually less than 7 per cent and the total mica content less than 12 per cent. The amounts of either or both types of mica seem to be quite independent of the anorthite content of plagioclase and of the orthoclase-plagioclase ratio, micaceous granodiorites being quite as common as micaceous granites.

There does seem to be a relation between mica and quartz, however, quartz-rich masses being relatively rich in mica (Fitzwilliam, Clark Island, Concord). The converse is also true, with the exception of Barre, which, though very rich in mica, is rather poor in quartz. Commonly in muscovite-rich granite much of the muscovite occurs as large euhedral flakes quite independent of plagioclase; at Barre, however, 90 per cent of the muscovite replaces plagioclase pseudomorphously (Chayes, 1950*a*).

All granites of the collection are calcalkaline, for the famous peralkaline quarry granites of New England (Quincy, Cape Ann, Peabody) are very coarse and were therefore not included in this sample. Perthitic intergrowths are never prominent, and the vast bulk of feldspar occurs in two readily distinguishable phases which seem to have formed quite as independently of each other, as, say, quartz and muscovite. In many sections, particularly those of muscovite-rich granites, muscovite and biotite are more prominently intergrown than are orthoclase and plagioclase.

Potash feldspar (the Or of the diagrams) seems to be mostly, and is perhaps entirely, microcline. Grains devoid of optical complexity occur in almost every thin section but are, on the whole, uncommon. Usually a wavy or indistinct grid can be made out under crossed nicols and often—in some rocks, almost invariably—the familiar microcline grill is clear and sharp.

Plagioclase was determined by X-ray spectrometer and γ-index in a suite consisting of two specimens from each of the major and most of the minor masses listed in table 1. The results of this work, which will be described in detail elsewhere, are summarized in table 2. The X-ray procedure (for which see fig. 5 and accompanying discussion in Tuttle and Bowen, 1950) is much quicker and potentially far more precise than the optical

method; and from the table it is clear that in this composition range both methods yield substantially the same results.

The optical work was done with a specially prepared series of oils, of indices 1.542, 1.545, 1.548, and 1.551, corresponding to An values of 9, 16, 24, and 31 (see Chayes, 1950*d*, eq. [2], p. 594). Determination of a particular γ-index as being, say, greater than 1.545 but less than 1.548 places the mineral in class B of the table without specifying an actual weight per cent of anorthite. The X-ray results, however, are read directly as numbers and their reproducibility is good except for very low An values; they are shown in table 3.

TABLE 2

COMPARISON OF X-RAY AND γ-INDEX DETERMINATIONS OF PLAGIOCLASE*

X-ray	γ-Index					
	A	B	C	D	E	$\Sigma_{(\gamma)}$
A	3	8	.....	.....	.....	11
B	.....	5	.....	.....	.....	5
C	.....	1	8	.....	.....	9
D	.....	.....	2	3	.....	5
E	.....	.....	.....	2	.....	2
$\Sigma_{(\gamma)}$	3	14	10	5	.....	32

* The classification of the plagioclase by letter is as follows:
A: An < 10, albite.
B: 10 ≦ An < 16, sodic oligoclase.
C: 16 ≦ An < 24, intermediate oligoclase.
D: 24 ≦ An < 30, calcic oligoclase.
E: 30 ≦ An < 36, sodic andesine.

With the recording procedure used in this work, the resolution of the instrument is very poor where An is low; values rendered uncertain by poor resolution are noted in table 3. Except for these, all of which are albites, each entry under "Individual Results" is the mean of three runs in excellent agreement with one another.

Sodic and intermediate oligoclase are clearly the dominant plagioclases, though neither albite nor calcic oligoclase is uncommon. Two important inferences may be drawn from the tables. It is evident from the "Individual Results" column of table 3, in which entries in the same line are for widely spaced specimens in each mass, that the anorthite content of plagioclase commonly exhibits only minor variation in most of these bodies. Agreement of the optical and X-ray results shown in table 2, furthermore, implies that extreme but small-scale variations, such as are occasioned by zoning or mantling, affect a very small portion of the total plagioclase in any given specimen. The "γ-index" of the table is simply the highest index observed, and, if zoning or mantling relations introduced extreme variations in composition in more than a small proportion of the total plagioclase, the An content indicated in this fashion would frequently be much larger than that given by X-ray. No large discrepancy of this sort was observed, and, though most of the "al-

TABLE 3

ANORTHITE CONTENT OF PLAGIOCLASE DETERMINED BY X-RAY SPECTROMETER

Area	Individual Results	Average
Westwood	1, 1	1
Waldoboro*	2, 10	6
Concord*	5, 7	6
Chelmsford*	3, 9	6
Hallowell*	6, 10	8
North Jay*	8, 12	10
Barre	10, 12	11
Woodbury	16, 24	20
Bethel	20	20
Pownal	19, 22	20
Bradford	20, 23	22
Fitzwilliam	21, 22	22
Westerly	21, 23, 24	23
Clark Island	19, 27	23
Milford	27, 29	28
North Sullivan	30, 33	32

* Values uncertain because of poor resolution.

bites" of the X-ray determination have maximum indices placing them in "sodic oligoclase," it is precisely in this composition range that the X-ray procedure is known to be suspect. The significance of both within- and between-specimen variations in An content of plagioclase is likely to be greatly exaggerated by the conventional qualitative descriptive techniques.

Although staining is not essential in discriminating between plagioclase and orthoclase, it saves much time and uncertainty in analysis. So far, no material clearly identifiable as orthoclase or microcline has refused to stain. Although it is possible to bring up a very faint stain in the plagioclase of some granites (e.g., Jonesport, Maine), this requires a deep etch. With an etch light enough to avoid damage to the thin section, I have found not a single grain of plagioclase which stained sufficiently to show color in transmitted light. The test is actually quite sensitive, so that potash must be very low in the plagioclase of these granites—if, indeed, it is present at all.

Most of the granites of the collection are white or gray, though, whenever there is the slightest excuse, quarrymen evidently prefer to call them blue, and "light blue" is the commonest commercial designation for stone of this type. Westwood is pink, as is the product of some of the Westerly quarries. The Westerly pink is often a buff tint and now passes commercially as "light flesh," though it was once called "swamp pink." The term "dark" as used in the quarrying industry refers to the shade of the polished face; an experienced quarryman can easily distinguish "dark" from "light" pieces in the rough state, though I am still unable to do so after much time spent in trying. The Barre granites, for instance, are usually graded for "darkness" at the quarry. A stone which polishes dark is always premium grade. The difference between light and dark polish is very striking, but, as far as I have been able to discover, it has no mineralogical significance at the present time. The original "Barre dark" was unusually rich in biotite, and in other parts of New England might have been called "black"; but the supply of this material was apparently exhausted many years ago, and it is now difficult to find specimens even on the grout heaps.

Just as the quarryman's use of "dark" has no direct reference to mineralogy, so his use of "fine" does not refer to grain size. A "fine" granite is simply one that yields a hard, smooth face and can be tooled in intricate and detailed patterns. With most of the granite called coarse by petrographers this is impossible. But it is also impossible with most of the granites we call "fine," e.g., Westwood or Pownal; and medium-grained granites, such as Barre, are sometimes remarkably "fine" in the quarryman's sense of the term. In every important petrographic property, including grain size, Barre and Woodbury are quite similar rocks, yet to the quarryman Barre is "fine" and Woodbury is not.

COLOR INDEX AND MICA CONTENT

The color index—or the *maximum* color index—of a granite is largely a matter of definition. But the definitions usually do not specify any exact sense in which this maximum is to be interpreted. The standard mineralogical classifications do not tell us whether the definition holds for an entire rock mass, a hillside, a quarry, a hand specimen, or a thin section.

The matter is of considerable importance here because color index was the only mineralogical criterion consciously

applied in obtaining the sample; the observation that the *mean* color index of any granite body studied does not exceed, say, 15 per cent, is quite as much a description of the sampling procedure as of the rock.

In most granites "black knots" or "heathen" are numerous. Sometimes, as in certain parts of the Clark Island granite, they may actually comprise as much as several per cent of the rock mass, but this is very rare. In any completely random sampling procedure a certain number of items in the sample would surely be black knots. It would be highly desirable to include specimens of this type, and their exclusion might even be regarded as a serious error if large samples were to be taken from each mass and the sampling could be performed without visual inspection. Unfortunately, neither of these conditions could be met, so the inclusion of knots, streaks, etc., in any of the samples would have occasioned serious difficulty in interpreting the results.

This point is perhaps worth some elaboration. Suppose that impurities of this sort comprise as much as 3 per cent of a given granite mass—an overgenerous estimate for most of the masses I have studied—and that a single hand specimen is to be taken from each of ten quarries in the mass. If one of these ten turns out to be a black knot carrying between 30 and 40 per cent biotite and practically no potash feldspar, it not only badly misrepresents the quarry from which it was taken but distorts the mean values for the whole group. Further, and most serious, it greatly enlarges the estimated dispersion for each of the major minerals. A single case of this sort might easily enlarge total within-group variances so much that intergroup differences otherwise highly significant would be obscured. If we then made the usual transition from the statistical conclusion that intergroup variance was not significant to the geological inference that the groups were, in fact, drawn from the same parent, we would be in serious trouble.

This could happen easily, even if inspection were no part of the sampling procedure. At present, inspection is a necessary part of the sampling procedure, however, so that to this hazard must be added the strong possibility of subjective bias in deciding how many knots are to be included from each mass. Under the circumstances, the only alternative seemed to exclude black knots, bands, gneiss enclosures, etc., from the sample, and this could be done only by rejecting specimens unduly rich in dark minerals. This criterion was applied with extreme caution; the rejection point was an estimated color index of 30 in a good-sized hand specimen, and in many cases hand specimens containing knots were collected and sliced. I tried to be sure that everything but the actual inclusions had some chance of appearing in the collection.[4] It is to be remembered, too, that, although a mineralogical criterion was used, it was applied to an entire hand specimen, whereas the final results are based exclusively on thin sections. If thin sections of a particular granite do exhibit very little variation in color index, I believe this is because the granite proper varies very little in color index, and not because color index has been arbitrarily restricted in the sampling procedure.

The heavy minerals of granite, though never abundant, are nevertheless astonishingly persistent. Even constituents of which no more than a few counts ever enter a single analysis are sometimes re-

[4] This same procedure was followed, incidentally, in excluding aplite and pegmatite, except that the criteria involved were nonmineralogical.

markably consistent. In Westerly, for instance, opaque accessories are almost invariably more abundant than nonopaques, whereas in Barre this relation is reversed. In either case a single widely discrepant value would have produced accessory means indicating an order of abundance opposite that shown by the great majority of thin sections. But in twenty-two thin sections of Barre and thirty-four of Westerly no such discrepancies occurred. Similar consistence is exhibited by most of the other granites, though it is, of course, less impressive in the smaller samples. The analytical procedure was aimed primarily at procuring reliable results for major constituents, and because of the count lengths the actual percentages of accessory constituents entered in the tables mean little. The analyses do suggest, however, that the amounts of accessories in a granite are likely to be highly specific. The results are summarized in table 4; only when the mean values are virtually identical does the consistent dominance of one constituent over the other vanish.

TABLE 4

RELATIVE DOMINANCE OF OPAQUE (o) AND NONOPAQUE (n) ACCESSORIES

AREA*	INDIVIDUAL THIN SECTIONS		AVERAGE VALUES (VOLUME PER CENT)	
	$o \geq n$	$o < n$	$\bar{o}$	$\bar{n}$
Westerly†	31	3	0.7	0.3
Bradford†	9	6	0.7	0.6
Westwood‡	0	8	0.6	4.5
Concord	2	4	0.2	0.4
Fitzwilliam	6	8	0.1	0.2
Milford	11	2	0.5	0.3
Barre†	2	20	0.2	0.8
North Sullivan	10	0	0.3	0.2
Clark Island	2	7	0.4	0.8
Pownal	2	12	0.1	0.2
Average§			0.4	0.8

* o and n not separately determined in Hallowell–North Jay and Woodbury.

† Data from Chayes (1950*a*, *b*). Remainder of table compiled from table 19 data.

‡ n includes much epidote replacing plagioclase.

§ Omitting Westwood, average $\bar{n} = 0.4$.

The commonest accessory minerals are magnetite, sphene, apatite, fluorite, carbonate, and tourmaline. Except in Bethel, epidote is largely confined to granites in which plagioclase has been extensively altered. Zircon is usually present, but always sparingly. Sulfides are commonly lacking and always very scarce. Other accessories are so scarce that precise identification in thin section is difficult and frequently impossible. Of the minerals so far named, magnetite, apatite, and carbonate are easily the most abundant. Fluorite is commonly conspicuous because of its color, but even where most deeply colored—and thus most prominent—it is probably less abundant by far than any of these three. Carbonate, incidentally, usually appears to be an alteration product but is almost never absent. Tourmaline is commonly brown and easily confused with biotite. The confusion can sometimes be avoided by careful study of individual grains, but this often requires a shift to higher magnification than that at which the analyses are run.

The only quantitatively important dark minerals are muscovite and biotite. The over-all averages, giving equal weight to each area, are 3.8 per cent muscovite and 4.8 per cent biotite. For individual areas the total mica content is never greater than 15 per cent, is greater than 13 per cent in only one case, and is usually less than 10 per cent. Except in Bethel, for which but a single slide is available, and in Westwood, the average total mica content is always greater than 5 per cent. As shown in figure 2 there seems to be no correlation between average values of the two; a rock rich in bio-

tite may be rich or poor in muscovite, and conversely. This lack of correlation persists within the separate masses despite common interlamination of the two minerals in thin section. An example is shown in figure 3.

It has already been mentioned that muscovite-rich granites are usually rich in quartz, the sole exception being Barre, where most of the muscovite is a pseudomorphous replacement of plagioclase. It is to be noted that Barre is also anomalously rich in total mica. A second exception to the high-quartz–high-muscovite association is Clark Island, the most siliceous of all the granites analyzed, which carries about twice as much biotite as muscovite (7.8 : 4.3) and is not unduly rich in either. These results are shown in table 5.

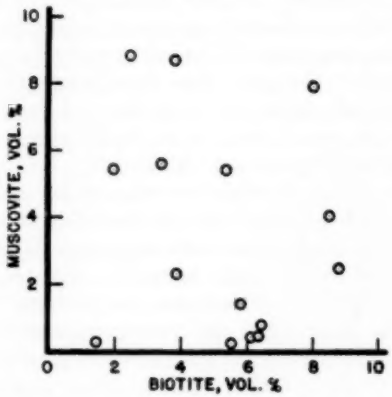


FIG. 2.—Average values for biotite and muscovite, volume per cent. Data from table 19.

There may be some tendency for granites unusually rich in muscovite to be unusually rich also in quartz. The total number of bodies for which sufficient data are available is still too small to permit adequate testing, however, and it is to be remembered that, even if the relationship were established, its inverse would not necessarily follow. Granites poor in muscovite are not necessarily poor in quartz, or conversely.

On the whole, members of the dark mineral group seem to be rather independent of major constituents. Whatever relationships may exist are so weak that their detection would require much more information. For this particular purpose the principal need would seem to be a considerable increase in the number of granite masses sampled rather than an increase in the number of samples per mass; relations within each mass are usually quite consistent, and often remarkably so.

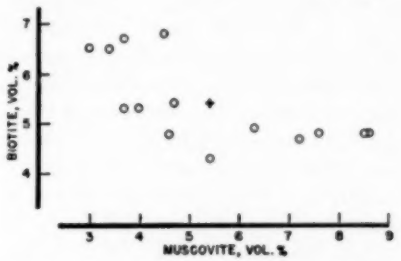


FIG. 3.—Biotite and muscovite values in thin sections of Fitzwilliam, New Hampshire, granite, volume per cent. Data from table 19.

TABLE 5

ASSOCIATION OF QUARTZ AND MUSCOVITE ABUNDANCES

	Rich in Muscovite	Not Rich in Muscovite	Total
Rich in quartz	3	1	4
Not rich in quartz	1	12	13
Total	4	13	17

QUARTZ CONTENT

Granites are defined in every classification as quartz-bearing rocks, and it is

well known that they usually contain much quartz. In some classifications the minimum quartz content is as low as 5 per cent, but a certain amount of hedging is apparent in the naming of rocks carrying less than 10 per cent quartz. Qualifying adjectives are often used where quartz content is less than 20 per cent and sometimes such rocks are not even called granite. The famous "quartz syenites" of the Adirondacks, for instance, frequently contain more than 10 per cent quartz. We like to suppose that classifications grow out of the objects being classified, but after long usage every classification tends to impose itself on its subject matter, and rock classifications are no exception. Practically every writer on the subject has insisted that the boundary between granite and quartz syenite is purely arbitrary. This statement has two rather sharply opposed connotations. It is, of course, entirely correct so long as we are classifying names. If we regard the system as a classification of rocks rather than names, however, the question of whether a boundary is arbitrary is a matter of fact and should be treated as such. If it turns out that feldspathic rocks with more than 15 per cent and less than 20 per cent of quartz are quite common, then any boundary in the region of 15–20 per cent is indeed unreasonable. If such rocks are actually very scarce, there is nothing arbitrary about the boundary.

There is a widespread sentiment, though the feeling no longer finds formal expression in any major classification, that in the calcalkaline series decrease in quartz is commonly matched by increase in color index, in anorthite content of plagioclase, and in the ratio of plagioclase to potash feldspar. This is obviously true as a matter of definition in any classification embracing all calcalkaline rocks; but what is true of the whole, even by definition, is not necessarily true of the parts. These parallel variations have never been convincingly demonstrated for any large group of granites, and nothing in the data here supports them. Bradford, Westerly, Pownal, and Barre, for example, are all rather poor in quartz, yet two are granodiorites, one is an adamellite, one a true granite; further, one has a very high color index, in two the color index is about average, in the fourth it is very low. Again, North Sullivan, Hallowell, Clark Island, Fitzwilliam, and Concord are all rather rich in quartz; yet three are adamellites, one is a granodiorite, one a granite; and the granite has a higher color index than the granodiorite. In the entire collection the rock with most quartz and most dark minerals (Clark Island) is an adamellite.

All the classifications seem under obligation to draw a line for the lower limit of quartz and then explain it away. With regard to the upper bound for quartz the situation is just reversed; few students of the subject are deeply concerned about the maximum quartz content of granite; yet in actual fact a quartz content greater than 45 per cent is almost never recorded, and values in excess of 40 per cent are rare. There are exceptions, of course, but in general quartz values greater than 40 per cent are to be viewed with extreme skepticism.

These restrictions on the amount of quartz are quite commonly regarded as matters of nomenclature—specimens carrying too much or too little quartz simply not being called granite—and I believe most geologists also feel that they apply strictly only to average values or bulk compositions. The data of table 19 go far to show that much more than a matter of names and averages is involved. It is to be remembered that individual entries in table 19 are not in any

sense average values or estimates of bulk composition. Each is a single analysis of a single thin section, each thin section is from a different hand specimen, hand specimens in any granite mass are widely spaced, and the granite masses themselves are scattered over some 20,000 square miles. Yet not a single quartz value is less than 20 per cent or more than 40 per cent; only three are in excess of 37 per cent, and most values of less than 25 per cent are from a single mass, Bradford, whose mean quartz content is only 24.3 per cent.

The leniency of classifications with regard to quartz content is quite unnecessary, and the impression created by it is misleading. A lower bound of 20 per cent and an upper bound of 40 per cent for quartz content would not be in the least unreasonable. With very rare exceptions, even individual thin sections of the finer-grained granites of New England may be expected to respect these limits. For average values, and presumably also for bulk compositions, the range may be even further contracted; all the mean values for these particular granites lie between 24 and 34 per cent.

Despite the small dispersion exhibited, significant differences in mean quartz content can be detected readily. Completely aside from its theoretical implications, this is a surprising and encouraging finding, for in many cases the samples involved are not much larger than those ordinarily accumulated in areal studies. It may be shown that quartz variances computed from table 19 are homogeneous, and this permits application of the conventional single-classification variance analysis to the data. The results are as shown in table 6; differences between group averages are easily significant in relation to variability within groups. This conclusion must not be read out of context. It does not mean that no two granites have the same quartz content, or that any two granites can be distinguished from each other by the tenor of quartz in small samples. It does indicate that the quartz content of granite is inhomogeneous and that even small samples may be adequate for detecting this inhomogeneity, provided that it is sufficiently extreme. A difference "sufficiently extreme" for this purpose need not be very large, however, for we have already seen that the *total* range of the means is only 10 per cent.

TABLE 6

VARIANCE ANALYSIS OF QUARTZ CONTENT*

Source of Variation	*df*	Mean Square
Between granites	19	47.46**
Within granites	125	5.014
$F = 9.46$	144	

* Data of table 19.

For descriptive purposes the point of maximum interest here is sample size. In general, very little can be accomplished with individual thin sections, for there is some overlap between the values shown for nearly every pair of the larger suites in table 19. Even samples considerably larger than those used here would not be adequate for discriminating between Milford and Westerly on the basis of quartz content, for the means differ by only 0.5 per cent. But a half-dozen specimens each of Pownal and Westerly would be ample to detect their difference in quartz content, a matter of some 2.2 per cent. In fact, if this were the only point at issue, larger samples would be uneconomical unless a precise estimate of the difference was required. As the difference itself is not large, the relative precision with which it is estimated increases rather slowly with sample size.

The narrow dispersion exhibited by quartz, whether in individual values or in means, is independent of sampling technique. In a general and rather crude fashion—just how crude will be apparent from a consideration of pages 226–230—it was known in advance that quartz was abundant in all these masses, but there was little reliable knowledge of its amount. The remarkably small variation of results for any particular mass was a complete surprise. It could not have been anticipated from previous work, and from current theories of granite origin just the opposite might have been expected. It was not forced by any quirk of the sampling scheme, for no hand specimen was ever accepted or rejected because of its apparent quartz content. In many of these granites hand-specimen estimates are impossible because of grain size. In my experience, even where grain size does not preclude the attempt, a guess about the amount of a mineral present in hand specimens is rarely worth making; major constituents can usually be distinguished from minor ones, but that is about all.

Very small range in quartz content within each mass and small but often significant differences between masses are evidently characteristic of the New England granites. I believe they are characteristic of finer-grained granites generally. Although modes are not now available, there is no reason to believe that quartz distribution will be any different in the coarse-grained granites.

THE Q-M-F DIAGRAM

It has been shown in the section "Color Index and Mica Content" that, if obvious inclusions are excluded from the sample, the color index of granites varies very little, even in areas as small as thin sections. A similar restriction on the range of quartz content was described under the heading "Quartz Content." These two results imply that total feldspar must also show comparatively small variation.

Now it may be argued that the limited range of feldspar, like that of color index, is again a property of the definition rather than of the rock, and the same defense is available. It is perfectly true that a rock very rich in dark silicates would necessarily be poor in feldspar and quartz. But we have no way of predicting in advance whether a rock poor in dark minerals will be either unduly rich or unduly poor in feldspar. It is usually neither. The grand mean for total feldspar is 60.4 per cent, and the group means all fall in a range of only 13 per cent. Variation within areas is also very small, as may be seen from table 19. Sharp upper and lower limits to feldspar content are evidently characteristic of the rock and hence ought to be included in any satisfactory definition. No individual analysis in the tables shows more than 68 per cent[5] of total feldspar and only three—all in Clark Island—show less than 50 per cent. No mean value is less than 53.2 per cent or more than 67.7 per cent. This spread is only a little larger than that found for quartz means, though feldspar is usually twice as abundant as quartz.

The results to this point are summarized in a series of ternary projections using total feldspar (F), quartz (Q), and dark minerals (M) as co-ordinates. Each of the larger groups is represented by a separate diagram (figs. 4–6 inclusive). Readers familiar with these granites will find that results for coarser rocks usually show more scatter than do those for the

[5] With more detailed work on Westerly and Bradford (Chayes, 1950*b*), however, a value of 69 per cent total feldspar was found in one section of Bradford, and 71 per cent total feldspar was recorded in one section of Westerly.

finer ones. Wherever possible, the diameter of each point is 1 per cent, approximately the analytical error for major constituents. The scatter is always larger than can be accounted for by analytical error, but by standards customarily applied both to rocks and to quantitative modes it must be regarded as, on the work. The hexagonal shape was adopted because it is easy to center. The small area was necessary because with larger counters the area enclosed by the zero contour was always large by a factor of at least 2. Even with such a small counter, however, the diagram shows a 9 per cent maximum. This is the equivalent of

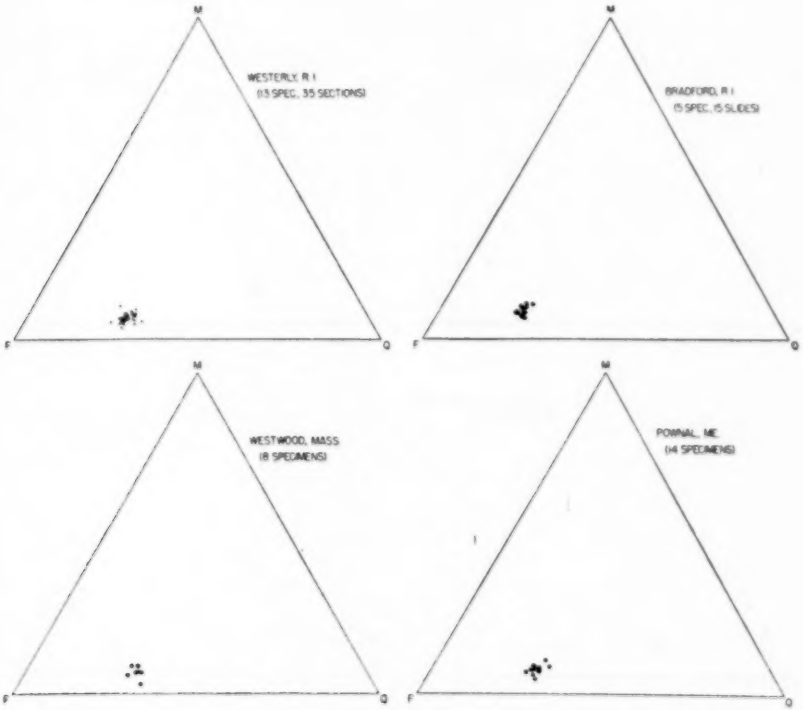


FIG. 4.—Volume per cent of quartz (Q), total feldspar (F), and dark minerals (M) in thin sections of Westerly, Bradford, Westwood, and Pownal granites. Data from table 19.

whole, astonishingly small. All the data for table 19 are shown in a single-point diagram in figure 7, and figure 8 shows the group means.

Figure 9 is a contour diagram prepared from figure 7. A hexagonal 1/8 per cent counter area was used in place of the 1 per cent counter usual in petrofabric a 72 per cent maximum with the conventional 1 per cent counter; the 9 per cent contour outlines an area 0.5 per cent of the total diagram area, containing 47 per cent of the points. The total occupied area of the diagram is only 4 per cent. Concentrations of this order are unknown in petrofabrics. Even the orienta-

tion of mica cleavage poles in schists does not approach it.

PLAGIOCLASE AND POTASH FELDSPAR

It has now been shown that color index and quartz content are in most cases highly specific characteristics and that the same is true of total feldspar, but so we seldom bother to determine with precision its color index or the relative dominance of its various dark minerals. But, if it has considerably more plagioclase than potash feldspar, we call it one thing; if it has considerably less plagioclase than potash feldspar, we call it another; and if the two types of feldspar are about

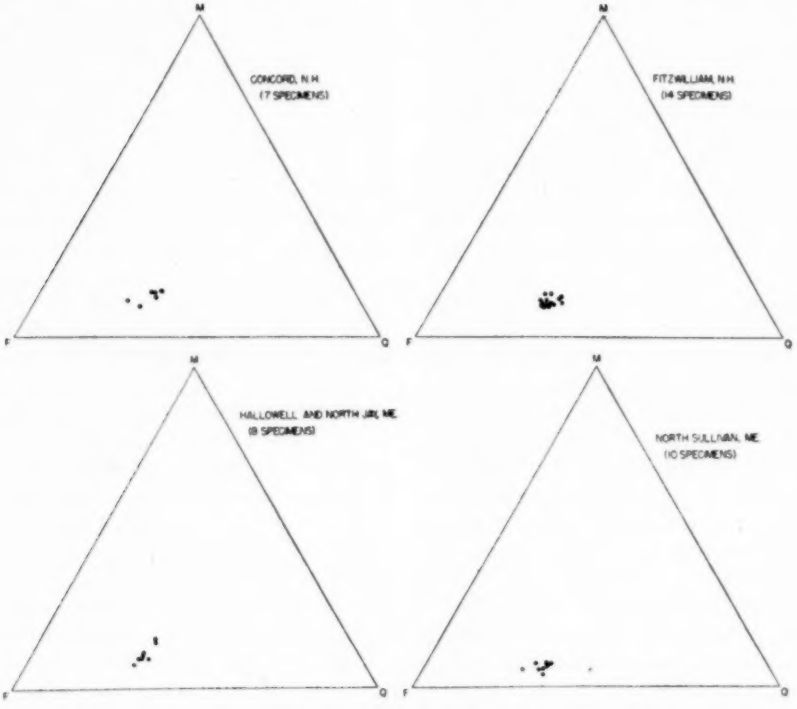


FIG. 5.—Concord, Fitzwilliam, North Jay–Hallowell, and North Sullivan granites. Co-ordinates as in fig. 4. Data from table 19.

far nothing has been said of the quantitative relations between the two feldspars. In most mineralogical classifications this relationship, whether obtained directly or by inference from chemical analysis, forms the principal basis for quantitative subdivision of the granites. In general, a granite may have as much or nearly as little quartz as it pleases, and equal in amount, many of us are likely to use still a third name. Whatever its logical or historical justification, the procedure turns out to be quite sound. The dominance of one feldspar over the other is quite as persistent as any of the mineralogical characteristics previously discussed, and between half and two-thirds of any granite is feldspar. Table 7 com-

pares feldspar dominance in individual specimens with area means. The results once more indicate an astonishing internal homogeneity. Statistical devices for assessing the "concordance" of thin-section results are available, but they could hardly add much to conclusions easily reached by inspection. In table 7 the areas are arranged in order of increasing difference between feldspar mean values. For very small differences there are, of course, almost as many slides of one type as of the other. But if the difference is greater than 2 per cent, a large majority of the slides falls into one of the two classes. For differences larger than 4 per cent the preponderance of one type over the other is overwhelming. There are nine cases in which the feldspar means differ by more than 4 per cent, and in seven of these the concordance of feldspar dominance in thin section is perfect. Here a word of caution is appropriate: results of this caliber must not be anticipated unless each thin section has been properly analyzed. Poor thin sections or slipshod analyses will not yield high concordance unless the mean difference is very large. Results based on inspection, on the other hand, may often indicate extreme concordance even where the mean difference is very small, but this concordance will frequently be entirely erroneous. Substantiation of these asser-

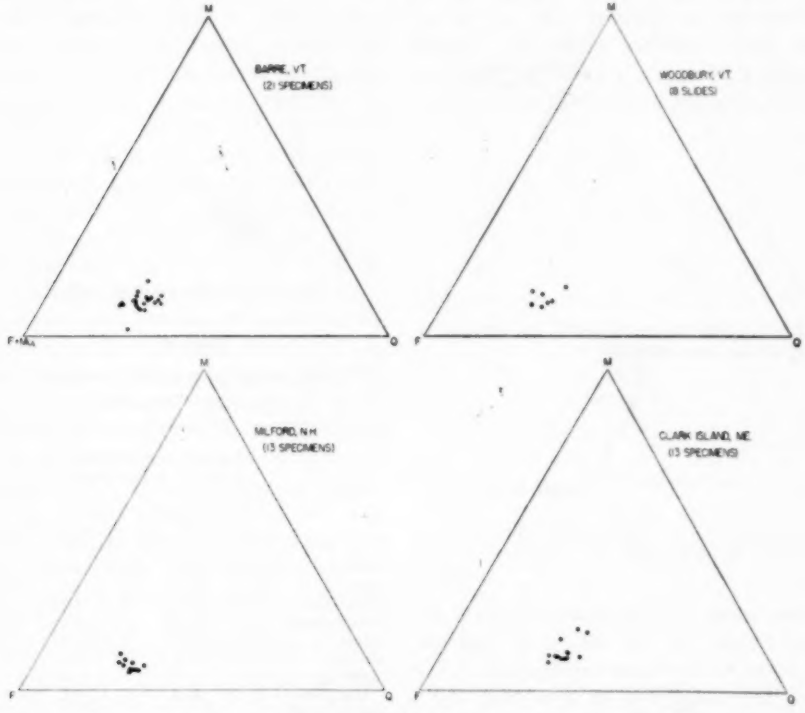


FIG. 6.—Barre, Woodbury, Milford, and Clark Island granites. Co-ordinates as in fig. 4. Data from table 19.

tions will be found under a subsequent heading, "Comparison with Previous Results." It would be misleading to present results like those of table 7, however, without a firm reminder that whenever the relative dominance of major constituents (or of minor ones) is a matter of importance, reliance on anything but careful analysis of first-class sections is an invitation to disaster.

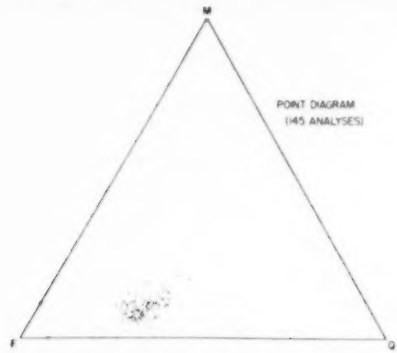


FIG. 7.—New England granites. Co-ordinates as in fig. 4. Data from table 19.

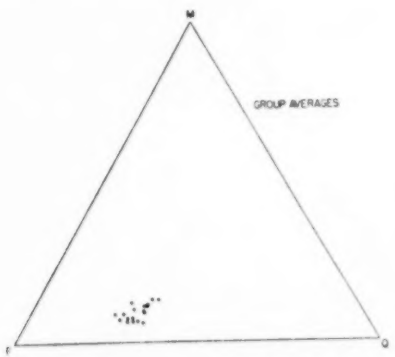


FIG. 8.—Group means from table 19. Co-ordinates as in fig. 4.

RELATIVE DOMINANCE OF QUARTZ, POTASH FELDSPAR, AND PLAGIOCLASE

The major constituents of all these granites are quartz, potash feldspar, and plagioclase. We have already seen that the quartz content of each mass is highly specific, and from the work of the preceding section it appears that the relative dominance of the two feldspars is usually quite consistent. Commonly, these three constituents are present in comparable magnitude, so that the relations of all three to one another are of first importance; as we shall see, they provide a

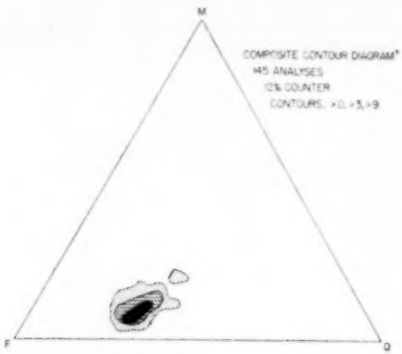


FIG. 9.—Contour diagram of fig. 7

TABLE 7

FELDSPAR DOMINANCE IN NEW ENGLAND GRANITES

AREA	MEAN VALUES		NUMBER OF THIN SECTIONS		|Or − Pl|
	$\overline{Or}$	$\overline{Pl}$	Or > Pl	Or ≤ Pl	
Westerly*	32.9	32.7	15	17	0.2
Concord	28.1	27.2	5	3	0.9
Fitzwilliam	27.6	30.3	4	10	2.7
Clark Island	25.2	28.4	3	12	3.2
Swanville	35.8	31.6	4	0	4.2
Milford	30.2	35.2	1	12	5.0
North Jay–Hallowell	31.7	26.4	6	2	5.3
North Sullivan	21.2	32.3	0	10	11.1
Pownal	38.4	25.2	14	0	13.2
Bradford*	27.1	40.6	0	15	13.5
Barre	19.4	35.2	0	21	15.8
Westwood	39.8	22.8	8	0	17.0
Woodbury	18.7	43.0	0	8	24.3

* Average values and frequencies taken from Chayes (1950b). All other data in the table are from table 19.

ready means of classification, except where differences between mean values are small in relation to analytical error.

The classification reached in this fashion is simply a ranking of the three major constituents in the order of their amounts. Letting 1 represent quartz, 2 potash feldspar, and 3 plagioclase, and mentioning each index number in its order of abundance, it is obvious that every granite—and every sample of granite—must fall into one of six classes. The classes are shown in figure 10. An analysis falling in class (123) is one in which quartz is dominant and potash spar exceeds plagioclase. In class (312), on the other hand, plagioclase is dominant and quartz exceeds potash spar.

If granites were invariant in composition, samples sufficiently large, and analyses sufficiently precise, all analytical results for a particular granite would fall into the same class as its true composition. Now the "true" composition is always unknown, and we are forced to use the mean of the analyses as an approximation of it; barring extremely erratic results, we may anticipate that this estimate of the true composition will fall into the most heavily populated class. To some extent, then, agreement between mean and modal classes is a matter of definition rather than observation. But the discussion of concordance can be carried through without reference to "true" composition, and the tendency toward a forced coincidence of mean and modal classes is heavily outweighed by other considerations. In the first place, far from being "large," the individual samples are very small. Second, the analytical procedure is far from precise, yet the variation in results for each mass is ordinarily larger than can be accounted for by experimental error alone. Despite these analytical and sampling difficulties, however, the concordance of results for each mass is usually extraordinarily high; it falls off only where differences between mean values are small.

Results for the larger groups[6] are shown in table 8 and may be examined graphically in figures 11–14 inclusive. The concordance is clearly of a very high order when differences between means exceed analytical error, and this proves to be the case in seven of the eleven masses for which sufficient data are available. In Westerly, quartz is appreciably lower than either feldspar and is

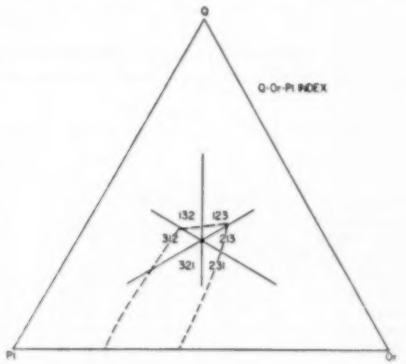


FIG. 10.—Q-Pl-Or diagram. Subdivision of granites. (*Q* = quartz, *Pl* = plagioclase, *Or* = potash feldspar.)

the least abundant of the three index minerals in thirty of the thirty-two slides; the feldspar means differ by only 2 per cent, and in individual analyses potash spar exceeds plagioclase as often as not.

In Concord, Fitzwilliam, and Clark Island, however, all three major mineral means are close together, and individual analyses may fall into any class. This situation arises only in quartz-rich granites, and it will be noted from the table that no case of extreme concordance oc-

[6] It is here that the inadequacy of the sample plan is most strongly felt, for it is obvious that concordance and discordance mean little where only a few specimens are available.

curs in classes (123) or (132). Where quartz is the dominant mineral, discordance seems to be the rule rather than the exception; where either of the feldspars is dominant, very high concordance may be anticipated. An explanation of the influence of quartz content on the feldspar concordance is offered in a later section.

COMPARISON WITH PREVIOUS RESULTS

The journal literature contains numerous modal analyses of many of the granites described above, and it was difficult to resist the temptation to combine these with the information in table 19. Indeed, this would have been particularly desirable for several of the smaller groups. After close study of the older analyses, I finally decided to rely only on my own work, a decision for which some justification is in order.

My own work has now been subjected to two rather rigorous tests. An extensive program of chemical testing has been carried through, with a strip of Westerly granite as sample.[7] Thin sections cut from this strip were stained and analyzed in exactly the fashion used to obtain the data for table 19. The average norm and mode are shown in table 9. The check is remarkably good as it stands. The principal discrepancy is in the feldspar figures, and here it is to be remembered that modal potash spar almost certainly contains a little soda and that some of the potash of the rock is present in muscovite —matters not taken into consideration in computing the norm. The coincidence between chemical and petrographic results is thus probably closer than the comparison of mode and norm indicates.

The precision of the modal result is also quite good. All the slides whose analyses are shown in table 19 have been analyzed at least twice, once before and once after staining, though only the second result is shown in the table. The

TABLE 8

CONCORDANCE OF THIN-SECTION ANALYSES, PRINCIPAL CONSTITUENTS

Area	Mean Values			Individual Specimens in Class						Total No. of Specimens
	Q	Or	Pl	(123)	(132)	(213)	(231)	(321)	(312)	
Concord	30.8	28.4	27.7	3	2	1	1	0	0	7
Fitzwilliam	31.0	27.6	30.4	1	5	3	0	1	4	14
Clark Island	33.2	24.2	29.0	2	6	1	0	0	3	12
North Jay–Hallowell	31.1	31.7	26.4	1	2	4	1	0	0	8
Westwood	30.6	39.8	22.8	0	0	8	0	0	0	8
Pownal	28.8	38.4	25.2	0	0	13	1	0	0	14
Westerly*	27.8	32.9	32.7	0	0	0	15	15	2	32
Bradford*	23.2	27.1	40.6	0	0	0	0	14	1	15
Milford	26.9	30.4	35.2	0	0	0	2	9	2	13
Woodbury	26.5	18.7	43.0	0	0	0	0	0	8	8
Barre†	27.2	19.7	35.4	0	1	0	0	1	19	21
North Sullivan	32.3	21.2	40.3	0	0	0	0	1	9	10

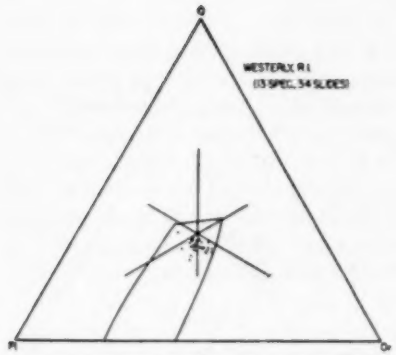
* For full data on Westerly and Bradford see Chayes (1950b, pp. 386–87). Table 19 gives only one analysis for each hand specimen.

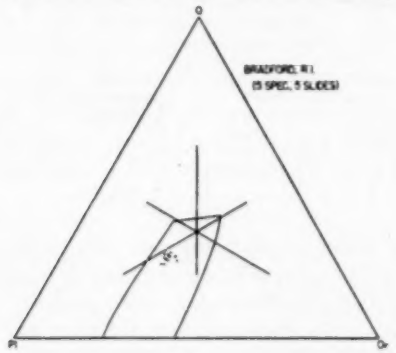
† If sericite replacing plagioclase were included with that mineral (see Chayes, 1950a), the single instance of (132) in Barre would be reclassified as (312), in which class nineteen of the other twenty sections already lie.

My own work has now been subjected to two rather rigorous tests. An extensive program of chemical testing has been carried through, with a strip of Westerly granite as sample.[7] Thin sections cut from this strip were stained and analyzed in exactly the fashion used to obtain the data for table 19. The average norm and mode are shown in table 9. The check is remarkably good as it stands. The principal discrepancy is in the feldspar figures, and here it is to be remembered that modal potash spar almost certainly contains a little soda and that some of the potash of the rock is present in muscovite —matters not taken into consideration in computing the norm. The coincidence between chemical and petrographic results is thus probably closer than the comparison of mode and norm indicates.

The precision of the modal result is also quite good. All the slides whose analyses are shown in table 19 have been analyzed at least twice, once before and once after staining, though only the second result is shown in the table. The

[7] This was a joint program of the Massachusetts Institute of Technology Geology Department, the U.S. Geological Survey, and the Geophysical Laboratory. The work at M.I.T. was supported by an ONR grant (Fairbairn and others, 1951).





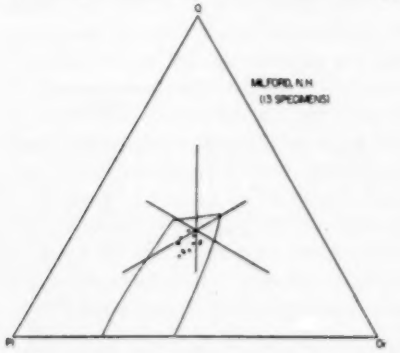
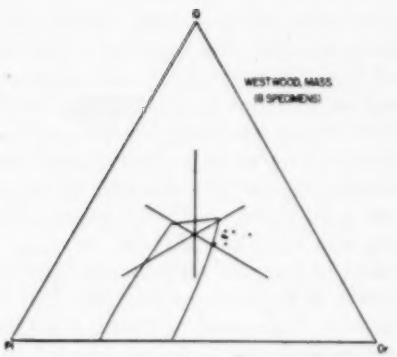
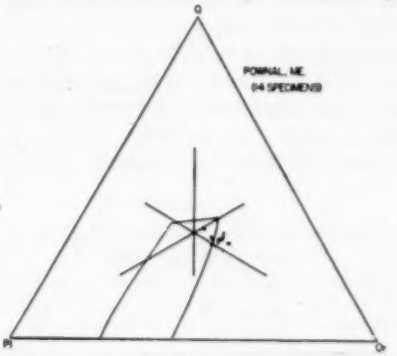


FIG. 11.—Q-Pl-Or diagrams for Westerly, Bradford, and Milford. Volume per cent recalculated to 100. Data from table 19 and from Chayes (1950*b*). Co-ordinates as in fig. 10.





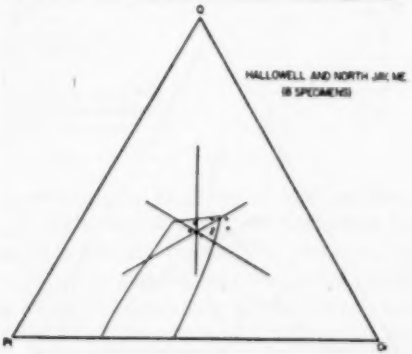
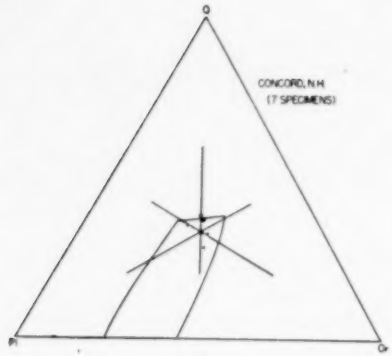
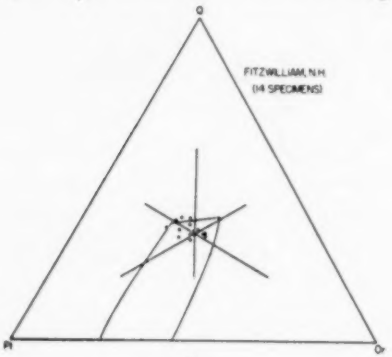


FIG. 12.—Q-Pl-Or diagrams for Westwood, Pownal, and North Jay–Hallowell. Volume per cent recalculated to 100. Data from table 19. Co-ordinates as in fig. 10.





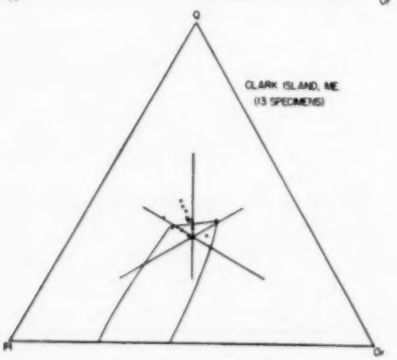
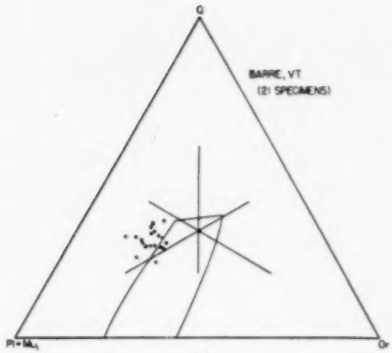
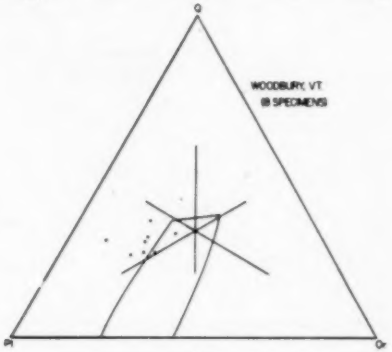


FIG. 13.—Q-Pl-Or diagrams for Concord, Fitzwilliam, and Clark Island. Data from table 19. Co-ordinates as in fig. 10.





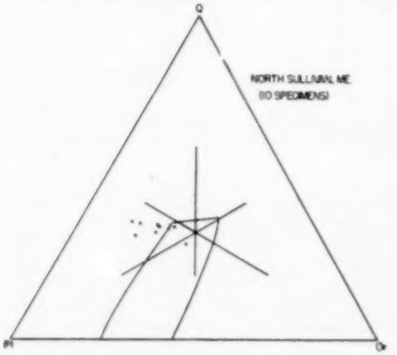


FIG. 14.—Q-Pl-Or diagrams for Barre, Woodbury, and North Sullivan. Data from table 19. Co-ordinates as in fig. 10.

Westerly, Bradford, and Milford slides have all been analyzed three times and the Barre sections four. In all this work there is strong evidence that the reproducibility of the method in the hands of a single operator is essentially as claimed (Chayes, 1949*a*). Recently, five of the thin sections of the test strip were analyzed by each of five members of the M.I.T. geology department. The average of their results is compared with my own

TABLE 9

MAJOR CONSTITUENTS, NORM, AND MODE OF WESTERLY TEST STRIP

Average Norm (32 Chemical Analyses)		Average Mode (16 Thin-Section Analyses)	
Quartz	28.6	Quartz	27.5
Orthoclase	32.5	Potash feldspar	35.4
Plagioclase	33.7	Plagioclase	31.4

average for the same five sections in table 10 (Chayes and Fairbairn, 1952).

Turning now to a review of previous results for the granites described in this paper, it will be convenient, first, to document the assertion of an earlier section that inspection is ordinarily not sufficient for a correct ranking of major constituents. Certainly, no student of American granites was better equipped for or more interested in such work than T. N. Dale. As often as he could, Dale made Rosiwal analyses, but in most of his work he was forced to rest content with a ranking of the type described in table 8, made, apparently, by inspection of thin sections or hand specimens.

His results are eloquent testimony to the inadequacy of this method. In reviewing them, it will be helpful to use the terminology developed in the discussion leading to figure 10. Dale describes eleven specimens of Westerly granite, placing eight in classes (132) or (213); not one of my thirteen falls into either of these classes. For Concord all eight of his specimens fall into (213); only one of my seven does so. For Milford eleven of his fifteen fall into (132); none of mine does so. For North Sullivan he records thirteen descriptions, all in class (213); none of my ten falls into this class. He records all his twenty-five Barre specimens as belonging in class (213); all but two of my twenty-two fall into (312), and none lies in (213). His seven specimens of Woodbury are placed in class (213), but all eight of mine are in (312). His classifications of North Jay and Pownal agree with the results of table 19, but he places Bradford in (312) instead of (321). All his descriptions of Fitzwilliam place it in class (213), whereas only three of my fourteen specimens fall into this class. It

TABLE 10

AVERAGES FOR FIVE SECTIONS OF THE WESTERLY TEST STRIP

Mineral	M.I.T. Group	Chayes
Quartz	27.2	27.1
Potash feldspar	35.1	35.0
Plagioclase	32.1	32.2
Muscovite	1.2	1.2
Biotite	3.2	3.4
Nonopaque accessory	0.4	0.5
Opaque accessory	0.8	0.7

is certainly no criticism of other aspects of Dale's work to point out that these results are highly misleading; one may go so far as to suggest that the rest of us are wasting our time using a procedure so unreliable in the hands of a worker as apt and devoted as Dale. As questions of sampling technique will no doubt be raised in opposition to much of the remainder of this section, it will be well to point out that they cannot be very serious in a comparison of Dale's work with mine. In every major area most of our

specimens are from the same quarries. Ranking of major constituents by inspection, whether of hand specimens or thin sections, is a thoroughly unreliable procedure.

That a composition is reported in numbers rather than in words, however, is no assurance of its reliability. Analyses of five of the granites included in table 19 were recorded by Shimer (1943) as an incidental part of his spectrographic study of New England granites and pegmatites. His results are quite different from

TABLE 11

AVERAGE MODES OF CONCORD AND FITZWILLIAM GRANITES

Mineral	Concord (Fowler-Billings)		Fitzwilliam (Table 19)		Concord (Table 19)	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Quartz	15.8	3.9	31.0	1.9	30.8	2.7
Potash feldspar	44.8	17.8	27.6	3.4	28.4	3.2
Plagioclase	23.6	18.2	30.4	2.8	27.7	2.0
Biotite	6.4	5.8	5.4	0.8	3.8	1.8
Muscovite	8.4	5.9	5.4	1.9	8.7	2.6
No. of specimens	14		14		7	

mine. At Barre, for instance, he reports 8 per cent less quartz and 10 per cent more plagioclase than I found in any of twenty-three specimens from that area, and, of course, his result differs from the mean shown in table 19 by much more than this. For North Jay he recorded 10 per cent more quartz and 10 per cent less plagioclase than the extreme values of table 19. His other results are similar. For the fifteen major constituent determinations in these five analyses, his results fall outside the *range* of mine in eleven cases. For two of these (North Jay and Waldoboro) my sample is so small that this is hardly critical. The Concord sample contains seven specimens, however, certainly adequate to give a first approximation of the expectable range; the Milford suite contains thirteen specimens, and the Barre suite twenty-two. As with Dale's rankings, the difficulty can hardly be ascribed to sampling; both of us used quarry material, and in each area rock from the quarry sampled by Shimer is represented in my collection. The differences are almost certainly due to inferior thin sections or to inadequate analytical procedure.

The remaining comparisons involve the possibility of variation due to sampling procedure. Mrs. Fowler-Billings (1949) has recently described the geology of the Monadnock region of New Hampshire. The principal granite of this area is called "Concord." It includes the "Fitzwilliam" granite of Emerson (1917), but its exact relation to the true Concord granite (e.g., the granite well exposed and extensively quarried in Rattlesnake Hill, Concord, New Hampshire) does not seem to have been established. Mrs. Fowler-Billings' results compare with mine for Fitzwilliam and Concord, as shown in table 11.

So far as quartz and potash feldspar are concerned, we might not even be talking about the same rock—and perhaps we are not. At first, I inclined to this view because many of Mrs. Fowler-Billings' samples are taken from the northern part of the area and, geographically at least, belong neither to Concord nor to Fitzwilliam. We have enough specimens in common, however, to indicate that our differences are not to be attributed to sampling. For specimens from the Webb quarry, Marlboro, and the Emerson quarry, Fitzwilliam, our results are compared in table 12.

Differences between these paired analyses are very similar to those shown by means of table 11. Both my specimens fall into class (312), while one of hers lies in (213) and the other in (231). Incidentally, her mean value (see table 11) falls into (231), a class unrepresented in my collection.

More disturbing than the lack of agreement between means is the extraordinary range shown by Mrs. Fowler-Billings' samples. In comparison with other analyses in table 19, those for Fitzwilliam

TABLE 12

MODES OF WEBB AND EMERSON QUARRY SPECIMENS

Mineral	Webb		Emerson	
	Fowler-Billings	Chayes	Fowler-Billings	Chayes
Quartz	18	31.5	10	28.6
Microcline	56	22.0	50	26.0
Plagioclase	15	35.8	25	33.6
Biotite	5	6.7	6	5.0
Muscovite	5	3.7	8	6.4
Opaque access.	.....	0.2	tr	0.3
Nonopaque access	tr	0.1	tr	0.3

are quite variable; standard deviations are among the largest calculated from the tables. Yet for each constituent the standard deviation in the second column of table 11 is very much larger than that in either the fourth or the sixth column. Were it clear from field data that all specimens actually came from the same mass, standard deviations of 18 per cent for potash feldspar and plagioclase would be fascinating. But when outcrop is as poor as it is in the Monadnock area and when all one knows about most specimens is that they are gray and come from the southwestern part of the state, assignment of such different rocks to the same "granite" amounts to abandoning mineralogy not only as an age criterion but also as a petrographic one. From the first and second columns of table 11 we are entitled to conclude that either feldspar may be lacking or present to the virtual exclusion of everything else in numerous specimens of this granite. From the remainder of the table it is quite clear that nothing of the sort occurs in the two localities where enough of the granite has been formed to warrant development of a major quarrying industry.

Quinn (1943) has described the concentration of heavy minerals at depth in the Bradford, Rhode Island, granite. He regards crystal settling as the process responsible for the effect and presents a number of thin-section analyses showing marked variation in major mineral content; gravitational stratification of early-formed crystals is also offered as an explanation for this second type of variation. In table 13 his results for major constituents are compared with mine (Chayes 1950*b*, p. 387; but for part of the data see table 19).

TABLE 13

MODES OF BRADFORD GRANITE

Mineral	Quidon		Chayes	
	Mean	Range	Mean	Range
Quartz	22.3	10–31	23.2	21.1–24.5
Potash feldspar	27.0	22–37	27.1	25.9–29.4
Plagioclase	40.1	33–45	40.6	38.2–42.8
Biotite	6.9	1–15	6.4	4.7– 7.3
No. of specimens	7		5	
No. of sections	7		15	

Agreement between mean values is obviously excellent; but, whereas my results place Bradford among the least variable granites in New England, Quinn's make it appear one of the most variable.

Some small part of this excessive variation may be attributable to inferior thin sections and perhaps also to analytical technique. Most of it, however, probably should be laid to sampling procedure. My specimens were taken without regard to location in the dike or to proximity of contacts with wall rock or enclosures. Quinn's, on the other hand, were taken across the strike from top to bottom, with strong emphasis on the margins. Barring this emphasis on the margins, which involves neglect of the central portion of the dike, it is clear that, if very large samples were to be used, the two procedures ought to generate not only identical means but also identical standard deviations for each constituent. With samples considerably smaller, but still much larger than petrographers are willing or able to use—with specimens taken, say, at every foot or yard through the dike—Quinn's procedure would probably yield more information than mine.

With genuinely small samples, however—of the size both of us happened to use—Quinn's procedure will almost certainly lead to a gross exaggeration of the range of composition of the mass and will hit on a suitable estimate of the mean or bulk composition only by a lucky chance. Any dispersion index calculated from his data is bound to be misleading, for the extreme variants he describes all occur at the outermost fringes of the dike, and from his diagram (Quinn, 1943, fig. 4) it appears that all but two of his thin sections were taken less than 3 feet from one or the other contact, though the total thickness of the dike is 65 feet. He thus has five samples from the outer 6 feet of the dike, and two from the central 59 feet; the variability of the main mass of the dike, whether systematic or not, can scarcely be estimated properly from his results. Now it is just this central portion of the dike that concerns us at present, for samples generated by any random sampling plan will contain, in the long run, about ten specimens from the central 59 feet for each one from the marginal 6 feet. Furthermore, it appears from Quinn's description that most of the lower and much of the upper 3 feet are probably not notably different from the central portion.

The bearing of this extended discussion on the decision to refrain from using older analyses is quite obvious. The ranking of major constituents by inspection seems thoroughly unreliable. For psychological reasons it will commonly yield a high concordance, but this concordance will usually be wrong. The fact that a composition is reported in numbers rather than in words is no assurance that it is any more reliable than an inspection ranking. Finally, even where there is no particular reason to question analytical precision, the type of information sought in the earlier work may have dictated a sampling pattern yielding results that cannot be integrated with the data of table 19, as in Quinn's study of Bradford. For these reasons, at the risk of appearing both ungrateful and hypercritical, I finally decided to use only my own results. I feel very strongly, however, that any competent petrographer should be able to turn out first-class thin-section analyses with little difficulty, and this view is certainly justified by the work of the M.I.T. group, briefly noted above.

AVERAGE COMPOSITION OF THE CALCALKALINE GRANITES OF NEW ENGLAND

In the quarrying industry the term "granite" is applied to almost any hard rock free of pronounced bedding or foliation, and, of all New England "granites," the least granitic, viz., the "black granites," which are usually gabbro or dia-

base, always bring higher prices than ordinary granites of comparable texture and hardness. Although there is ample technological justification for this use of the term, geologists are inclined to regard it with amused and tolerant disapproval. It is obvious that a granite is not a gabbro even if the two occur in the same township or quarry. If rocks were to be as loosely defined as this, there would be no point in describing them and no hope of discovering their origin.

Our primary objection to the quarryman's definition is that it brings together under a single name rocks of very different composition. We may also cite differences in habit, fabric, and mode of occurrence. In the final analysis, however, we could not refuse to call an unbedded eucrystalline rock "granite" if it contained abundant quartz, potash feldspar, and moderately calcic plagioclase, together with subordinate amounts of mica, amphibole, or pyroxene.

In our own way, however, many of us stretch the term quite as recklessly as the quarryman. Where he wants to include gabbro, diorite, diabase, or syenite, some geologists want to throw in schists and gneisses. Indeed, in recent years the distinction between granite and metamorphic or even other intrusive rocks has been either carelessly ignored or purposely denied. This tendency is perhaps nowhere better epitomized than by Dr. Read's (1948) suggestion that we use a dictionary definition. His dictionary happens to omit plagioclase, a fact he deplores, but in mine (Funk and Wagnall's *Desk Standard* [1935]) he would have found that a granite is "a rock composed of quartz, feldspar and mica," which may be interpreted as including both types of feldspar. Now every student who has survived a few weekly quizzes in elementary geology knows that amphibole ought to be added to this list and that, if it were, the "group" so defined would include not only most of the granite in the world but also most of the schist and gneiss. Small wonder that we have failed to agree about the origin of a rock as diverse as this! And hardly surprising that, working from this definition and feeling that most granites are "of one kind, and all of them may likely be of one connected origin," Read seems to regard most granite as nonmagmatic. He has, in fact, only two avenues of escape from such a conclusion. He might suggest either that schists are magmatic or that his chosen definition is so broad and loose as to be meaningless.

This dilemma arises from admitting composition as a qualitative basis for classification but denying it quantitative status. The quarryman ignores composition entirely and in New England comes to use the term "granite" as a synonym for "igneous rock." The antimagmatist specifies broadly that "granite" is a rock composed of certain very common minerals and thus lumps it with many metamorphic rocks composed of the same minerals.

The problem of setting quantitative limits for the composition of granite is by no means simple, and the approach taken here is entirely empirical. From the very broad class of rocks known to New England quarrymen as granite, only those have been excluded (purposely) which were too coarse for reasonably economic thin-section analysis or which, like the "black granites" of Clark Island, Addison, Calais, etc., no geologist could admit as granite without important qualifications or reservations. The limits suggested below leave a comfortable margin at each end of the observed range of average compositions of the remainder. This procedure is open to obvious criticisms. The mineralogy of most of the coarse

New England granites is similar to that of the finer-grained ones, but it happens that one very famous peralkaline granite, the Quincy, quarried extensively at Quincy, Rockport, Cape Ann, and Peabody, has been omitted because of grain size. From the work of Warren (1913) the average modal composition of Quincy granite seems to be well within the limits specified below for quartz content, total feldspar content, and color index. These limits are intended to apply only to the binary calcalkaline granites of New England; I believe they will ultimately be found adequate not only for other calcalkaline granites but for alkali-granites as well. At present, however, this is mere speculation.

Exclusion of schists and gneisses from the sample may invite much criticism. With regard to schists, the explanation is very simple. However geologists may feel about the subject, a schist is not called a granite in the New England quarries. In Connecticut, however, several gneisses have been quarried and marketed as granite, and these certainly deserve careful examination. The whole question of how (and when) to distinguish gneisses from granites is quite troublesome in work of this sort. Approaching the problem about the way it would be approached by anyone trained during the thirties, I first assumed that the sharp distinctions insisted upon by earlier workers would prove unfounded and that a study of granites must eventually become—in fact, probably would be from the start—a study of gneisses. This turned out to be completely wrong. Some evidence of structure is apparent in many hand specimens of granite, but it is almost invariably very weak. One probably should call Chelmsford a "gneissic granite" or "granitic gneiss," though the analyses have been retained in table 19 because of current interest in the rock. In certain quarries, Fitzwilliam tends to be rather gneissic. Elsewhere structures prominent enough to suggest the use of "gneiss" or "gneissic" in the rock name seem to be of purely local origin and extent. This is not to say that calcalkaline granites are always devoid of orientation, or even that they are commonly so. The fact that a rock possesses orientation of some sort, however, is not sufficient justification for calling it a gneiss; as much confusion can be created in this fashion as by Read's suggestion that any rock composed of quartz, orthoclase, and mica be called "granite." The pronounced foliation and banding which one has a right to expect in properly named gneisses are strikingly absent from the calcalkaline granites of New England. Micas often seem to show a weak "foliation" but are almost never concentrated into definite laminae. The other minerals (quartz and feldspars) are so intricately intergrown and of such complex outline that no grain orientation is clearly visible; usually one feels quite safe in asserting that grain orientation is absent, though, of course, it is entirely possible that lattice orientation exists in many of these granites. After much study of quarry faces, grout blocks, hand specimens, and thin sections, I can recall no case of perceptible compositional banding of quartz and the feldspars; the only cases of such banding affecting micas are local and appear to result from incomplete digestion of inclusions. Yet both types of banding are prominent in the gneisses which are commonly cut by and included in these granites, i.e., at Milford, Bradford, or Westerly, and true schistose lamination is well shown by inclusions in North Sullivan, Clark Island, and many others. It seemed sensible, therefore, to confine the initial sampling

to rocks whose grain orientation or composition banding was too weak to require mention in naming; these rocks under control, it would be time enough to move on to more complicated species.

Now it is quite probable that some gneisses fall within the specified composition limits, and it is even remotely possible that most of them do so. It is also possible that gneisses of such composition are more abundant than nongneissic granites. The simple fact is that we do not know and will not know until students of the subject are ready to buckle down to work on a long, hard job. The quantitative modal composition of common metamorphic rocks is of vast importance, and our ignorance of it is stupendous. All of us should feel responsible for occasional forays into this field. The burden of proof, however, is clearly upon those who maintain that schists and gneisses are either gradationally transitional to, or essentially identical with, granite. Meanwhile, it is fair to point out that only very deep students of the subject will be able to confuse the calcalkaline granites of New England with the country rocks in which they occur. Whether they are igneous rocks or not is for the reader to decide; they do not possess the common attributes of schist or gneiss, however, and nothing is gained either by pretending that they do or by ignoring this obvious distinction.

With due reservation and qualification, the rocks described in this paper are easily the commonest and most abundant—though certainly not the only—representatives of the granite clan in New England. Clearly, their composition is or should be a matter of critical importance to any theory of granite origin. From the preceding discussion, much of which argues that many of these rocks can readily be distinguished from one another by modal analysis, it is obvious that there is no *single* New England calcalkaline granite. Except possibly for geophysical uses, a grand mean cast up from table 19 would have little significance. In most of the individual areas, however, specimens have been drawn from what may be seen or safely inferred to be either continuous or closely related rock masses. The exact dimensions of these masses are not known. Probably none is of the magnitude of the textbook "batholith," though even the smallest is a considerable volume of rock, at the very least on the order of many millions of cubic yards. The reasonably inferred volume of the larger masses is surely of the order of several cubic miles; depending on one's definition of "reasonable," it may be much more than this. Though separated from each other by some 10 or 15 miles, the Barre and Woodbury granites are very similar in composition, and it is entirely credible that they are parts or offshoots of the same subjacent mass. The Fitzwilliam and Concord granites of New Hampshire are virtually identical in composition, though they are more than 50 miles apart and most of the intervening county is under heavy cover. In Maine, Hallowell and North Jay are again virtually identical, though separated by more than 25 miles. Even if our concept of "reasonable" is not generous enough to include the possibility of subterranean connections between such widely spaced bodies, the individual masses themselves are still large, and sometimes enormous, volumes of material.

An average value for each mass may thus be regarded as an estimate of the value most likely to be found in future random samplings, single or multiple, from the same or different sites, of the particular rock concerned. We may also

regard it as an estimate of the bulk composition of the rock available to observation. Accustomed to the exorbitant and often highly successful extrapolation contained even in fairly simple geological maps, we will no doubt be willing to suppose that averages for each mass are representative of much more than the rock we can actually see or sample. This extension of results to material we cannot hope to examine is inescapable; without it there could hardly be a science of geology. We must continually bear in mind, however, that, except in areas of extreme relief, we never have direct evidence bearing on the question of whether or not granites persist, either unchanged or merely without sharp break, to great depth. In two dimensions, our sampling may often be as good as we choose to make it; except for a thin veneer at the very top of the lithosphere, however, the third dimension is pure guesswork.

The work of the preceding sections provides an excellent basis for generalizations about the composition—whether "bulk" or "expected"—of the exposed portions of the rocks described. As these rocks differ from the great mass of New England calcalkaline granite only by virtue of having been quarried, we may use the generalizations to describe the expectable range of composition of granites of this type. Bearing in mind that the range under discussion is of *mean* values, and *not* of individual samples of any given mass, we may thus set up provisional limits for the composition of New England calcalkaline granites.

The average composition of such a rock will include between 20 and 35 per cent of quartz. Values in the central portion of this range will be far more common than those at the extremes; the observed mean values all lie in the range 23.6–33.2 per cent, with only one less than 26 per cent and, of the larger groups, only two greater than 32 per cent.

A New England calcalkaline granite will be not less than half or more than very slightly over two-thirds feldspar. The feldspar will invariably be of two distinct types—microcline (orthoclase) and plagioclase (albite to calcic oligoclase); perthite will be uncommon and quantitatively unimportant. Of the total feldspar, not less than one-third and very rarely more than two-thirds will be plagioclase. The ratio of either feldspar to the other will thus nearly always be less than 2:1. Of the granites for which more than one thin section has been analyzed, this ratio is greater than 2 in only one case (2.5, Woodbury), and in only three others (North Sullivan, Barre, and Westwood) is it greater than 1.6.

The essential heavy silicates will always be biotite and muscovite, the former usually in excess of the latter; neither hornblende nor pyroxene will be abundant, for both seem to be confined either to contact facies[8] (hornblende at Clark Island) or to inclusions from which they may have been derived (both minerals at Westwood and Clark Island). The minimum values for quartz and total feldspar set forth above are such that their occurrence in the same rock would leave a deficit of some 30 per cent to be filled in by dark minerals. In actual fact this does not seem to occur; the highest recorded color index (including muscovite as a "dark mineral") is 17.7, at Barre, and the second highest is 13.7, at Clark Island. Conversely, if the highest recorded average values for quartz and total feldspar occurred in the same rock, there would be no room at all for other

[8] The better-known hornblende granites of New England are peralkaline. In Texas and the Southeast, hornblende is also very uncommon in calcalkaline granites.

minerals, but the lowest color index recorded is 6.2, at North Sullivan. The total observed range is thus only 11.5 as compared with a possible range of about 30. Color index is never very high, but dark minerals are never either lacking or very scarce.

Summarizing these estimates, the average or bulk composition of a New England calcalkaline granite should not fall outside the following limits: quartz, 20–35 per cent; total feldspar, 50–70 per cent; color index, 5–20; and ratio of dominant to subordinate feldspar, $\leqq 2.5$. In general, it will lie in the central portion of each range.

May we turn this description into a definition and say that any (New England) rock whose composition falls within the specified limits is a calcalkaline granite? Or are the schists and gneisses indistinguishable from, or transitional to, the granites, as the antimagmatists urge? No amount of speculation or haphazard observation can satisfactorily answer this question; without the data of table 19, we would be in no position to raise it. With this information we can see at once that an answer based on adequate sampling and analytical technique would go far toward resolving the granite controversy, at least for this portion of the earth's crust. It would be a long, hard job, but surely one worth while.

VARIABILITY OF A FINER-GRAINED NEW ENGLAND CALCALKALINE GRANITE

Variability in the composition of individual samples of any rock has little meaning apart from sampling technique. When each item in the sample is a thin section of fixed area, it is obvious that variability will be to some extent a function of grain size. That thin sections of a coarse-grained rock vary widely in composition is not to be taken as evidence that the rock itself is highly variable; it probably shows only that a single thin section is an inadequate sample. On the other hand, a single thin section will contain several hundred grain sections of a fine-grained rock; and, if thin sections of such a rock vary greatly, it can only be a reflection of similar variability in the rock.

The rocks described in this report were all classed by Dale (1923, p. 9) as fine, medium fine, or medium. Despite this limitation, grain size does appear to influence dispersion, coarser rocks like Barre, Woodbury, or Clark Island varying more from thin section to thin section than finer ones like Westerly or Pownal. A full discussion of this complex effect is not possible because there is at present no adequate quantitative definition of grain size. The problem is further complicated by the fact that the *total* range of composition of thin sections of any particular granite is usually rather small; isolation and estimation of some part of it attributable to grain size alone will be a sizable task.

By the same token, because total variation is small, we can afford to postpone analysis of purely experimental factors which contribute to it. In the discussion which follows, it is to be understood that each analysis is of a thin-section area not less than $\frac{3}{4}$ inch or more than 1 inch square; that each such area is continuous and simple in outline; that the slides are of high quality, uncrushed, and free of holes; and that the grain size of the rocks involved is not greater than "medium" in Dale's terminology.

Where variances are homogeneous, the best estimate of internal variation is obtained by pooling estimates for each of the subgroups. Such a pooled estimate has already been made for quartz and appears as the "within-granite" mean

square in table 6. The standard deviation for "within-granite" variation is simply the square root of this mean square, or 2 per cent. The 4s range for quartz in thin sections of any particular granite is thus only 8 per cent. Allowing a considerable margin for error in the estimate of this standard deviation, a difference as large as 10 per cent between quartz values for two slides of any one of these granites would be very rare, and differences as great as 7 or 8 per cent would be quite uncommon. Quartz is easily the least variable of the three major constituents, both within and between granites.

very local affair, and a similar tendency might escape detection in the finer-grained rocks; it is worth noting that even in the finer-grained rocks the range for each feldspar is nearly always slightly, but appreciably, broader than is that of either total feldspar or quartz. The rocks of table 14 appear to have very little in common beyond grain size. They vary widely in average potash-feldspar content. Although three of them fall in the same class (312), the most spectacular example, Clark Island, belongs in (132), and in Hallowell potash feldspar is the dominant major constituent. In

TABLE 14

INFLUENCE OF DISCREPANT VALUES ON RANGES OF POTASH FELDSPAR

Area	Mean Or	Discrepant Or	Total Range Or	Range Omitting Discrepant Or	Class of Granite
Woodbury	18.7	8.9	16.3	8.7	(312)
Barre	19.7	12.5	12.7	9.8	(312)
North Sullivan	21.2	30.8	17.6	12.7	(312)
Clark Island	24.2	6.8	26.9	13.9	(132)
Hallowell	31.4	23.5	13.5	6.8	(213)

Rather serious difficulties arise when similar calculations are attempted for potash feldspar and plagioclase. Variances for these minerals turn out to be inhomogeneous largely because of the occurrence of single widely discrepant potash feldspar values in five of the groups. These erratic values influence group means very slightly, but, of course, they greatly enlarge the range or other dispersion index. Their effect on range is shown in table 14. In four of the five cases the discrepant value is drastically lower than its group mean; in the fifth it is considerably higher. These rocks are among the coarsest in the sample. The occasional extreme depletion (or enrichment) of potash feldspar seems to be a

Woodbury, Clark Island, and North Sullivan biotite greatly exceeds muscovite. In Barre the two are present in about equal amounts, and in Hallowell muscovite is greatly in excess of biotite. Finally, color index is low in North Sullivan, intermediate in Hallowell and Woodbury, and high in Barre and Clark Island.

The slack produced by this abrupt and local depletion of potash feldspar is largely taken up by plagioclase, with the result that feldspar variances are rendered inhomogeneous and feldspar ranges are unduly enlarged in five of the twelve groups by results for only five thin sections in a total of one hundred and forty-five. Even including the discrepant results, the ranges of potash feldspar and

plagioclase shown in table 19 are less than a third as large as one would suppose from available earlier analyses. If these five highly erratic results are eliminated, the range of either feldspar seems to be invariably larger, but usually not very much larger, than that of quartz.

Turning next to internal variations in total feldspar content, it is obvious from a glance at figures 4–6 that the total quantity of feldspar is highly specific. A variance analysis of the data of table 19 is given in table 15. (The calculations include only granites for which five or more thin sections are available.) Differences between groups are highly significant. More to the point, however, is the estimate of range which may be obtained from the smaller mean square, as has been done already for quartz. Two thin sections of the same granite—provided that the granite is not coarser than medium in Dale's scale—should very rarely differ by as much as 12 per cent in total feldspar content. In table 19 ranges as great as this actually occur only in Barre and Clark Island; four of the twenty-two thin sections of Barre may be formed into four pairs which differ by more than 11 per cent in total feldspar; and from the twelve Clark Island slides, five such pairs may be formed.

TABLE 15

VARIANCE ANALYSIS OF TOTAL FELDSPAR CONTENT*

Source of Variation	Degrees of Freedom	Mean Square
Between granites	12	222.38**
Within granites	118	8.57

* Data from table 19.

THE EXISTENCE OF GRANITE MAGMAS

The theoretical implications of this work have been briefly summarized elsewhere (Chayes, 1950*c*). From the remarkably small variation of color index and quartz (or total feldspar) content, as shown on the Q-M-F diagram (figs. 4–6), the existence of a homogeneous parent-material for each granite body may be inferred; and, from the very small difference of color index and quartz (or total feldspar) content as between granites (see figs. 7–9 and accompanying discussion), it may be argued that differences in composition between the various parent-materials must have been slight. There is no question, however, that differences between the rocks are often highly significant, though small, and it is impossible to avoid the inference that this was also true of the parent-materials, at least immediately prior to formation of the rocks. As far back as we can follow it, the granite parent was not a single material with a single composition; rather it was a group of closely related distinct materials.

The more fashionable geological speculations would prefer to substitute the concept of a homogeneous process for the inference of a homogeneous parent, as it is obvious that, once we admit the existence of the parent, we have to decide what it was, and we might decide that it was magma. This is exactly what we shall do, but first it will be well to enlarge a little on difficulties common to the whole suite of nonmagmatic hypotheses, and perhaps particularly critical for the transformists.

The average composition of granite shown in figure 8 has been public knowledge for more than fifty years—is, in fact, partly a matter of definition, though rarely of direct mineralogical observation—and in some fashion every hypothesis manages to account for or to ignore it. The only novel element in the

figure is that the results on which it is based have been obtained cheaply, relatively quickly, and without benefit of chemical analysis. As has already been stressed, however, *the data points of figures 4–7 and 9 are in no sense averages.* Each point is a plot of the result of a single analysis of a single thin section less than 1 square inch in area. So far as it "represents" any real quantity of rock in other than a purely statistical sense, the relevant volume is not that of a stock or a quarry or even a hand specimen; it is at most the volume of a single thin section, perhaps one-thousandth of a cubic inch and less than 50 mg. in weight. This absurdly small sample is taken in the worst possible fashion, with no sifting, rolling, or homogenizing of any sort. Furthermore, in the data of figures 7 and 9, no two thin sections are from the same hand specimen, and most of the hand specimens are from different quarries widely scattered over New England. A mixing so thorough as to defy the imagination has been done for us before we take our sample, and this is one of the most important properties of New England calcalkaline granites.

According to nonmagmatic hypotheses, the formation of granite is itself a mixing process. A granitizing agent (ichor, emanations, clouds of ions) penetrates and reacts with a heterogeneous mass of sediments and metamorphic rocks. The pre-existing rocks take just what they need from the invading medium and surrender to it exactly what they do not need. The end-product is granite. It is practically impossible to discuss a process of this type in terms both general and meaningful, but we can make some progress if we are willing to consider variations exhibited by some constituent abundant both in the pre-existing rocks and in the end-product.

Sandstone and quartzite, for instance, are a common part of any sedimentary or metamorphic complex. Schuchert (1931) estimates that they form about 25 per cent of the sediments of the Appalachian trough, and we may use this as a first approximation for New England (it makes little difference whether the correct value is 20 or 30 per cent). From the work of Tallman (1949) we would anticipate that nearly half this material carried over 95 per cent of quartz and that in about two-thirds of it the quartz content was over 75 per cent. Of a little over two hundred analyzed thin sections of New England granites in my collection, not one carries as much as 40 per cent of quartz, and in only three is the quartz content over 36 per cent. What has become of the sandstones and quartzites? Evidently they are gone without trace. Would we not anticipate that a feldspathization process so extreme would overshoot a little, forming here and there minute patches (of the order, say, of a few square inches or parts of a square foot) of syenite? It does not seem to, and any such patches which do occur must be extraordinarily rare. So far I have not found a single thin section of New England granite containing less than 20 per cent quartz. What kind of feldspathization process is it that works perfectly wherever it finds more than 40 per cent of quartz and fails completely when it reduces the quartz content to 20 per cent? Such a process operating on a very coarse scale and only in terms of average or bulk compositions is hard enough to credit. What are we to say when it works at a scale of square inches of area, on volumes of the order of a thousandth of a cubic inch, in a region notable for its remarkable petrographic heterogeneity?

Unreasonable as all this seems, something of the sort must be involved in each

of the nonmagmatic granitizations of highly siliceous sedimentary or metamorphic rocks. To the extent that this is so, I believe we must discard them outright as explanations of the origin of these particular granites. A similar argument might be made out for other minerals, particularly biotite, muscovite, and total feldspar, but it would necessarily be more tedious and less persuasive, because reliable quantitative information about the modal composition of metamorphic rocks is virtually lacking.

A uniform process could hardly generate such results unless it were working on a uniform material, and we return, therefore, to the concept of a homogeneous parent-material for each of these granite masses. The parent-material must differ, either in composition or in state, from the granite as we know it. From the granites themselves, we have no evidence suggesting marked compositional change and very strong reason for supposing that the composition of the immediate parent of each mass must have differed little, if at all, from that of the final product. The major event separating any one of these granites from its immediate parent was evidently a change of state. If it was not once a gas, it must have been a liquid, and there is, as usual, no evidence that it was gaseous. By exclusion, we thus arrive at a liquid of approximately the same composition as the finished product for the homogeneous parent-material of each of these masses, and there is no reason why we should longer refrain from calling this liquid "magma." By common practice we continue to use the name "magma" until the change of state is essentially complete, and the term thus includes its original denotation of "porridge" or "paste." The important matter, however, and one that we must not evade by relying too heavily on etymology or usage, is the conclusion that, if any one of these granites was ever not a granite, our evidence is strongly to the effect that it was a liquid of granitic composition.

So far this selection of a liquid or magma as the most likely parent-material has been justified only by the elimination of other possibilities. A consideration of the relation between quartz, potash feldspar, and plagioclase now provides more positive justification.

Figures 11–14, which show the proportions of quartz, potash feldspar, and plagioclase found in thin sections of individual granite masses, contain two sets of reference lines. The three intersecting straight lines at the center of each figure divide it into six subtriangles, each delimiting one of the classes of figure 10. The potential utility of these classes as a descriptive device is obvious from a glance at the figures. Concordance, as measured by the tendency for analyses of a particular granite to concentrate in some class or adjacent pair of classes, is remarkably high. Major constituent concordance has already been described at considerable length under the heading "Relative Dominance of Quartz, Potash Feldspar, and Plagioclase," and it is the second set of reference lines, outlining a slanted rectangular field extending upward from the base line to a little past the center of the triangle, which is germane to the present discussion. This is, of course, the silica-rich end of the thermal valley in the system nepheline-kaliophilite-silica. Its significance has been admirably described by Dr. Bowen (1937), who showed that (*a*) fractional crystallization of a liquid of basaltic composition would generate residual liquids lying in or near the thermal valley and (*b*) in the vast majority of cases, compositions of individual glassy rocks or averages for

felsic rocks of many different types do in fact lie in or very near the thermal valley.

Our argument has nothing to do with glassy rocks, average values, or fractional crystallization of basaltic liquid; yet the distribution of values for each individual granite mass shows a curiously systematic relation to the thermal valley.

For certain granites, as shown in figure 11, all results lie in the valley. There are three examples of this type in the sample: Westerly and Bradford, Rhode Island, and Milford, New Hampshire. In each of the other nine New England granites for which sufficient data are available, some points lie outside the valley, but in only one (Westwood, Massachusetts) are they all outside. Thus in eight of the nine cases there is some overlap of the valley boundaries, and the nature of this overlap is highly critical, for, *in any particular granite, values lying outside the valley are all on the same side of the valley.*[9]

In the granites of North Jay–Hallowell, Maine, Westwood, Massachusetts, and Pownal, Maine, outlying values are all on the orthoclase side of the valley (fig. 12). In the granites of Fitzwilliam and Concord, New Hampshire, and Clark Island, Maine, overlap is in the quartz field (fig. 13). In the granites of North Sullivan, Maine, and Barre and Woodbury, Vermont, overlap is exclusively on the plagioclase border of the valley (fig. 14).

In every one of these nine cases, a reasonable shift of the ternary mean would have generated overlap on two sides of the valley. In three of the nine, dispersion is easily large enough that a rather small shift of the ternary mean, depending on its sense, would have generated either a two- or threefold overlap. Yet the single overlap is the only type so far observed.

By any of the nonmagmatic hypotheses, this effect can only be regarded as a chance event. So far as these hypotheses are concerned, there is no reason for the points to be concentrated in the center of the diagram at all, and values for any particular granite might fall outside the valley on any one side, on any two sides, or on all three sides. Of these seven possibilities, only three are realized, and all are of one type, the single overlap. Because of the variability of dispersion, no exact probability can be attached to this event. A rather large scatter is required for a triple overlap, whereas the width of the valley clearly sets a maximum value for cases of no overlap. If single and double overlaps are taken as equally likely, however, the probability of obtaining nine of one type and none of the other is only 0.002; and, even if single overlap is considered twice as likely as double, this probability is still only 0.026. The correct answer is probably somewhere between these limits and is certainly small enough so that any satisfactory hypothesis of granite origin must regard the observed frequency of single overlap as something more than a chance event. Having discarded the concept of a parent-liquid, nonmagmatic theories can hardly explain the observed distribution in terms of crystal ⇌ liquid equilibria.

For magmatic hypotheses, however, the situation is entirely different. The observed distribution of Q-Or-Pl values is reasonable and almost necessary. If exceptions to it were anything but rare, magmatists would have to conclude that either their theories were wrong or their

[9] A few minor exceptions should be mentioned. Of a total of twenty-two thin sections of Barre, results for two lie not only well to the left of the plagioclase margin of the valley but slightly above the boundary of the quartz field. This is true also for one of the eight slides of Woodbury and two of the ten slides of North Sullivan. In all four cases the discrepancy is considerably smaller than analytical error.

experimental techniques faulty. Crystallization of a liquid whose initial composition lies in the diagram generates a liquid residue which approaches and finally enters the thermal valley; and, unless heat is added, the liquid cannot escape from the valley, once it has entered. The composition of adequate samples of such a crystallizing mass would necessarily fall either in the valley or outside it on the side nearest the initial composition. The observed distribution is thus thoroughly compatible with the hypothesis that granites form by crystallization of magmas (liquids) of granitic composition.[10]

It is important to emphasize that this conclusion is based on the entire assemblage of data and not on measurements for any one granite body. As a corollary, the mere fact that measurements for one granite body are of this type certainly does not prove that body to be of magmatic origin; the single case takes on importance only when considered along with the other eleven. The more such examples accumulate, the more likely does it become that granites of this type are quite generally of magmatic origin, but, even if a very large number of them do accumulate and no exceptions at all are found, we shall never be able to "prove" that any *particular* granite is magmatic because of its composition. Isolated examples of granites having the right distribution of Q-Or-Pl values but clearly or allegedly of nonmagmatic origin are thus not critical counters to our argument.

In parrying Nockolds' somewhat similar argument about aplites, Miss Reynolds (1947, p. 214) seems to overlook this distinction between a general and a particular conclusion. She points out that she herself has described a case in which veins of the appropriate magmatic composition appear to have formed in the appropriate transformist fashion. Nockolds (1947) is concerned that compositions compatible with magmatic origin are found in 63 aplite analyses, but he nowhere denies that such compositions might sometimes be found in aplite formed according to the transformist dispensation; Miss Reynolds' discovery that this may indeed have happened in a case known to her is therefore quite irrelevant. Nothing less than the announcement that aplites of the composition noted by Nockolds are *not* particularly common will provide a successful transformist rebuttal to his argument.

In exactly the same way, the conclusion we have been discussing is general, not particular. It is likely and even possible that among granites formed by nonmagmatic processes there would be cases of both single and no overlap of the boundaries of the thermal valley. The only effective counter to the argument, however, would be the announcement that *other* relations to the thermal valley, viz., double and triple overlap as well as

[10] The "thermal valley," of course, is outlined by Bowen only for the pure system albite-orthoclase-quartz, whereas in each of these granites plagioclase contains some anorthite, and potash feldspar probably carries some albite. The effect of these impurities on the position of a point in the Or-Ab-Q projection will usually be rather small. As an example, if we suppose that a particular specimen contains equal amounts of quartz, plagioclase, and potash feldspar, the potash feldspar containing 10 per cent Ab and the plagioclase carrying 20 per cent An, its co-ordinates before and after correction for these impurities in the feldspars would be as shown in the accompanying tabulation.

	Q	Or	Ab
Before correction	33.3	33.3	33.3
After correction	35.6	32.2	32.2

This difference would hardly be perceptible in a ternary diagram the size of fig. 11. Ideally, the correction should be made with data obtained from each specimen. At present, however, there is no reasonably economical way of obtaining the necessary information about the albite content of potash feldspar.

complete separation from it, are actually very common.

Isolation from the thermal valley due to extreme enrichment in potash is the only one of these anomalous relations which has so far attracted much attention. Graphic granites (Nockolds, 1947, table 3) commonly lie well within the orthoclase field. A summary of other analyses exhibiting similar potash enrichment has recently been presented by Riad Higazy (1950), who cites two cases of volcanic rocks in which the analyses may be regarded as a measure of the variation encountered either in a single rock mass or in bodies which may be offshoots of the same subjacent mass. Both cases (Homestake, South Dakota, and Esterel, France) are certainly extreme; but, though there is no doubt something queer about the Esterel rhyolites, their composition is known only from analyses of dubious quality.

By searching Washington's tables, Higazy has managed to find 59 individual analyses situated in the quartz or orthoclase fields, and most of these are well away from the estimated margins of the thermal valley; 40 of the 1,233 analyses in britannare and 19 of the 399 in columbare fall in this category. The absolute scarcity of such analyses is partly a matter of ignorance. Their relative rarity can hardly be explained in this fashion, however, for it is a commonplace that the rarer rocks receive far more than their fair share of attention.

THE ROLE OF MUSCOVITE IN THE LIGHT OF THE MAGMATIC HYPOTHESIS

In most of these granites, muscovite —more properly white mica—is of two types. It may form flakes scattered indiscriminately through the rock quite independently of feldspar, and in this case it is frequently interbladed on the (001) face with biotite. On the other hand, in almost every slide a little muscovite (sericite) replaces plagioclase, and in many rocks replacement material of this sort accounts for a large proportion of the total muscovite content. There is no sharp distinction between these two types of occurrence, and, where the replacement material is abundant, as in Barre, muscovite interbladed with biotite may be seen to extend into and psuedomorphously replace adjacent plagioclase in almost every thin section. It has been suggested (Chayes, 1950*a*) that, as it seems to occur throughout the mass and in direct ratio to the *original* quantity of plagioclase, this remarkable pseudomorphous replacement of plagioclase by mica in the Barre granite must have taken place before any pronounced separation of crystallized material and residual liquor. Until the residual liquor has been segregated or used up, we are pretty well obligated to call the liquid-crystal mush a magma, and the replacement reaction should therefore be considered late-magmatic.

If the residual liquors have been notably concentrated in some portions of the magma chamber and eliminated from others before the reaction takes place, the magma, as a homogeneous parent-material, has ceased to exist. If the extent of the reaction seems to be independent of the amount of replaceable material (original plagioclase) and varies inversely with the *surviving* plagioclase, we may safely assume that this was the case. This is probably what most of us have in mind by the term "deuteric," though quantitative data for such a discrimination between "deuteric" and "late-magmatic" replacements are usually not available.

Now whether we label a particular replacement deuteric or late-magmatic,

even in this rather restricted quantitative sense, may frequently depend on how we define the magma or its chamber. Very large and carefully distributed samples of the granite exposed in and near the Barre quarries might unearth some tendency for local concentration of end-stage liquors prior to the muscovite-plagioclase reaction. The tendency is evidently very weak, however; so long as we work with a sample no larger than that shown in table 19—perhaps even if we work with one two or three times as large—it will likely escape detection. We shall have no evidence that the reaction is other than late-magmatic.

TABLE 16

AVERAGE COMPOSITIONS

Mineral	Barre	Woodbury
Quartz	27.2	26.5
Potash feldspar	19.7	18.7
Plagioclase	35.4	43.0
Muscovite	7.9	2.4
Biotite	8.0	8.8
Others	1.8	0.6
No. of specimens	21	8

If intuition or sound geological evidence permitted us to regard the granites of Barre and Woodbury as parts of, or offshoots from, the same subjacent mass, the situation would be quite otherwise. The average compositions of these two rocks are shown in table 16. The major difference between the two is that Barre is several per cent richer in muscovite and several per cent poorer in plagioclase; the Barre plagioclase is a highly sodic oligoclase (An_{11}), whereas that of Woodbury is An_{20}. The total quantity of muscovite in Woodbury is too small to permit its subdivision into replacement and nonreplacement types without very extended analysis. But probably not more than half the Woodbury muscovite replaces plagioclase, whereas 90 per cent of the Barre muscovite does so. Finally, if we may be old-fashioned enough to make the usual interpretation of a chilled rock, the composition of a very fine-grained microporphyritic aplite which forms a large horse in the Rock of Ages Quarry at Barre tells us what might have become of the Barre-Woodbury magma if it had managed to complete its crystallization promptly, before conditions rendered the plagioclase-muscovite reaction possible. This composition is shown in table 17.

The Barre-Woodbury magma contained a certain amount of potash; and, if this potash had been permitted to do so, evidently nearly all of it would have formed feldspar. When crystallization proceeded slowly, however, plagioclase became unstable before this could occur,

TABLE 17

COMPOSITION OF APLITE FROM ROCK OF AGES QUARRY

Mineral	Insets	Insets as Per Cent of Total Rock	Total Rock
Quartz	23.4	4.6	26.6
Potash feldspar	None observed	.....	25.2
Plagioclase	59.3	11.7	40.8
Muscovite	None observed	.....	0.9
Biotite	17.3	3.4	5.4
Others	None observed	.....	1.0

and potash, which might otherwise have appeared in one feldspar, went to form muscovite, replacing the other. The granite therefore contains less of *both* feldspars than the aplite.

This is no doubt a much oversimplified version of the situation. We do not know whether muscovite becomes stable when or because plagioclase becomes unstable or whether the latter of these alternatives puts the cart before the horse. We cer-

tainly cannot say that potash feldspar and muscovite may not form together in granite. Potash feldspar usually begins and ends its crystallization very late, and it would seem reasonable that, in the absence of disturbing factors—e.g., the presence of unstable plagioclase—there would be considerable overlap in the stability ranges of the two.

Finally, the whole argument is based on the convenient but surreptitious assumption that Barre and Woodbury are products of the same magma. If the distance of 15 miles separating them frightens the skeptical, we have only to turn to the closely studied state of New Hampshire for a far more extreme leap. The granites of Concord and Fitzwilliam have been regarded as identical for mapping purposes since the earliest state survey (Hitchock, 1877, vol. 2, p. 24, cited by Fowler-Billings, 1949, p. 1270), though the main quarries are separated by more than 50 miles and much of the intervening country is under heavy cover. Average compositions of these granites, drawn from table 19, are shown in table 18. The largest differences are again in muscovite and plagioclase; Concord is richer than Fitzwilliam in muscovite by a little over, and poorer in plagioclase by a little less than, 3 per cent. These differences are small, and, as an isolated case, their significance would surely be in doubt; in the light of the Barre-Woodbury results, however, they are highly suggestive. As in the Barre-Woodbury comparison, the more calcic plagioclase (An_{22}) occurs in the muscovite-poor rock, while the plagioclase of Concord is very sodic (An_6).

TABLE 18

AVERAGE COMPOSITIONS

Mineral	Concord	Fitzwilliam
Quartz	30.8	31.0
Potash feldspar	28.4	27.6
Plagioclase	27.7	30.4
Muscovite	8.7	5.4
Biotite	3.8	5.4
Others	0.5	0.3
No. of specimens	7	14

The finer-grained members of the entire sample (Westerly, Bradford, Westwood, Milford, Pownal) are all very poor in muscovite, but relatively rich in total feldspar and, with the exception of Bradford, in potash spar as well. Unless crystallization is fairly slow, muscovite has very little chance to form at all. On the other hand, conditions which render mica stable at the expense of plagioclase are likely to prevail throughout all of what can be seen to be a continuous mass of calcalkaline granite in New England. If these indications are correct, determination of whether the reaction is to be regarded as late-magmatic or deuteric in a particular case would seem to depend more on comparisons between masses than on extremely detailed studies of individual masses, as was previously suggested (Chayes, 1950*a*). The problem is evidently one in which the distances concerned are to be measured in miles rather than in yards. Much more work of both types will be required, however, before a satisfactory solution emerges.

THE ORIGIN OF GRANITE MAGMAS

As soon as we decide that there are granite magmas, our first inclination is to guess about how they form; and, if we pursue the inquiry very far, we are almost sure to find that, whereas basaltic magma may be as "primary" as you please—which means simply that most of us agree not to worry about its origin—granitic magma must be in some fashion "derivative" or "secondary." Yet, if we admit the existence of granitic magma at all, we are obliged to confess that it

TABLE 19

MODAL ANALYSES OF NEW ENGLAND GRANITES

Area	Specimen No.*	Quartz	Potash Feldspar	Plagioclase	Biotite	Muscovite	Opaque Accessories	Nonopaque Accessories
Rhode Island and Massachusetts:								
Westerly†	1	26.6	32.4	34.6	4.2	1.2	0.9	0.1
	2	29.2	32.0	33.2	3.6	2.4	0.4	0.2
	3	29.2	30.3	32.5	4.3	2.7	0.7	0.3
	4	27.1	32.3	33.7	3.4	1.8	1.4	0.3
	5	28.9	29.4	32.5	3.4	4.7	0.8	0.3
	6	27.9	34.3	29.0	2.6	4.9	1.0	0.3
	7	26.8	30.9	34.2	3.9	2.9	1.2	0.1
	8	25.6	36.2	31.7	2.9	2.2	1.0	0.4
	9	27.7	35.5	32.2	2.9	0.8	0.8	0.1
	10	26.5	28.7	36.8	5.8	1.5	0.4	0.3
	11	23.8	26.8	38.9	6.8	1.9	0.8	1.0
	12	27.1	37.4	30.3	4.1	0.5	0.5	0.1
	13	30.0	29.5	34.6	2.1	2.3	0.3	1.2
Average		27.4	32.0	33.4	3.8	2.3	0.8	0.4
Bradford†	1	23.1	26.1	40.9	5.9	2.2	0.7	1.0
	2	23.4	27.6	41.0	6.1	0.4	0.6	0.9
	3	24.5	24.7	39.9	6.9	2.4	0.5	1.1
	4	24.4	26.0	40.2	6.1	2.3	0.5	0.5
	5	22.6	26.3	41.6	7.1	1.3	0.5	0.6
Average		23.6	26.1	40.7	6.4	1.7	0.6	0.8
Chelmsford	1	32.3	34.6	21.0	2.6	6.8	n.d.‡	2.7
	2	29.4	33.5	30.0	1.4	4.1	n.d.	1.6
Average		30.8	34.0	25.5	2.0	5.4	n.d.	2.2
Westwood§	1	30.5	39.5	23.4	1.4	0.4	0.5	4.3
	2	28.8	40.8	24.8	1.6	0.0	0.5	3.5
	3	31.0	45.2	17.0	1.3	0.1	0.9	4.5
	4	30.3	37.6	23.5	1.7	0.3	0 5	6.1
	5	32.0	40.6	20.9	1.3	0.5	0.5	4.2
	6	33.6	39.9	23.5	0.4	0.1	0.6	1.8
	7	28.3	36.9	26.3	1.8	0.7	0.7	5.3
	8	30.0	38.3	23.2	1.4	0.4	0.5	6.2
Average		30.6	39.8	22.8	1.5	0.3	0.6	4.5
New Hampshire:								
Milford	1	30.7	29.1	32.7	6.1	1.0	0.2	0.2
	2	24.1	30.6	36.5	8.0	0.3	0.1	0.4
	3	28.1	33.8	31.6	5.3	0.6	0.4	0.2
	4	29.9	31.4	32.6	5.0	0.2	0.7	0.2
	5	27.6	28.8	38.0	4.3	0.2	0.7	0.4
	6	27.5	28.7	37.7	5.1	0.1	0.9	n.d.
	7	24.9	32 0	35.3	6.6	0.4	0.4	0.4
	8	27.2	34.0	32.2	5.3	0.4	0.5	0.4
	9	29.1	28.4	36.2	4.4	0.9	0.6	0.4
	10	27.2	32.4	33.8	5.9	0.2	0.4	0.1
	11	22.2	29.0	37.2	9.9	0.7	0.6	0.4
	12	24.4	29.5	36.5	8.0	0.3	0.5	0.8
	13	26.9	27.4	37.0	7.9	0.1	0.6	0.1
Average		26.9	30.4	35.2	6.3	0.4	0.5	0.3

* For location of specimens see table 20.
† For further analyses of Westerly and Bradford specimens see Chayes (1950b).
‡ Not detected.
§ Nonopaque is mostly epidote and carbonate replacing plagioclase.

TABLE 19—*Continued*

Area	Specimen No.*	Quartz	Potash Feldspar	Plagioclase	Biotite	Muscovite	Opaque Accessories	Non-opaque Accessories
Concord	1	33.2	26.4	26.1	4.0	9.9	0.1	0.3
	2	32.5	29.0	25.7	3.4	8.7	0.3	0.2
	3	30.6	24.8	30.5	2.5	10.6	0.4	0.6
	4	25.4	32.4	30.6	1.9	9.4	0.2	0.1
	5	31.7	27.3	27.0	6.8	7.0	0.2	
	6	29.6	32.9	27.7	5.6	3.7	0.3	0.2
	7	32.9	26.2	26.3	2.5	11.5	0.1	0.5
Average		30.8	28.4	27.7	3.8	8.7	0.2	0.3
Fitzwilliam	1	32.7	27.4	29.9	4.3	5.4	0.1	0.2
	2	28.7	27.9	30.0	4.8	8.5	n.d.	0.1
	3	33.5	25.9	28.0	4.8	7.6	0.1	0.1
	4	34.5	24.3	30.6	5.4	4.7	0.4	0.1
	5	31.5	25.7	33.3	4.8	4.6	n.d.	0.1
	6	29.3	26.4	34.5	5.3	4.0	0.1	0.4
	7	30.4	32.2	28.1	5.3	3.7	0.2	0.1
	8	28.1	29.3	31.1	4.9	6.3	0.1	0.2
	9	30.7	29.3	30.0	6.5	3.0	0.2	0.3
	10	29.9	31.9	26.8	6.8	4.5	n.d.	0.1
	11	29.3	32.9	27.5	6.5	3.4	0.1	0.3
	12	33.1	22.9	32.1	4.7	7.2	n.d.	n.d.
	13	30.2	29.0	27.3	4.8	8.6	0.1	n.d.
	14	31.5	22.0	35.8	6.7	3.7	0.2	0.1
Average		31.0	27.6	30.4	5.4	5.4	0.1	0.2
Vermont:								
Woodbury	1	28.1	19.1	42.3	9.1	1.1	0.3	
	2	29.2	25.2	34.6	5.9	4.6	0.5	
	3	30.8	16.5	37.1	10.4	4.2	1.0	
	4	24.0	20.4	45.4	8.8	0.5	0.6	0.3
	5	22.2	16.9	46.7	11.9	1.6	0.7	
	6	27.2	19.3	44.1	8.7	0.7	n.d.	0.1
	7	26.4	8.9	51.4	10.8	1.9	0.6	
	8	24.1	23.1	42.8	4.6	4.6	0.1	0.7
Average		26.5	18.7	43.0	8.8	2.4	0.6	
Barre‖	1	26.6	18.2	38.6	6.3	8.5	0.1	1.7
	2	31.2	17.6	32.4	9.3	8.0	0.2	1.3
	3	31.6	17.3	35.2	9.1	4.5	0.1	2.2
	4	32.7	20.0	32.1	8.0	5.8	0.1	1.3
	5	24.7	23.5	32.3	8.5	8.9	n.d.	2.1
	6	22.5	18.7	39.7	7.0	9.7	0.1	2.3
	7	26.4	23.8	33.5	6.2	8.1	0.3	1.7
	8	29.2	21.1	33.9	6.4	8.2	0.2	1.0
	9	20.8	23.8	38.8	7.9	6.9	0.1	1.7
	10	30.8	17.7	32.6	9.4	8.3	0.2	1.0
	11	25.1	18.8	36.1	9.4	9.4	0.1	1.1
	12	24.8	19.7	35.8	9.6	8.3	0.3	1.5
	13	28.0	15.4	38.3	7.5	9.1	n.d.	1.7
	14	29.0	18.8	33.0	9.1	8.1	0.2	1.8
	15	27.4	24.8	36.6	0.2	9.8	0.1	1.1
	16	25.8	21.2	32.6	7.1	11.2	0.4	1.7
	17	25.4	20.4	30.3	16.0	6.8	0.1	1.0
	18	27.9	17.6	37.6	6.3	9.3	0.1	1.2
	19	28.6	18.5	33.5	7.7	9.1	0.3	2.3
	20	24.3	18.3	35.9	11.1	8.0	0.5	1.9
	21	27.9	12.5	40.4	8.7	7.9	0.4	2.2
	22	26.6	25.2	40.8	5.4	0.9	0.1	0.9
Average		27.2	19.7	35.4	8.0	7.9	0.2	1.6

‖ For more detailed results on Barre see Chayes (1950a).

TABLE 19—*Continued*

Area	Specimen No.*	Quartz	Potash Feldspar	Plagioclase	Biotite	Muscovite	Opaque Accessories	Nonopaque Accessories
Bethel	1	28.0	5.1	60.7	0.2	3.4	0.6	2.0
Maine:								
Pownal	1	29.2	36.2	27.2	5.1	2.0	n.d.	0.3
	2	28.7	38.9	26.5	4.7	1.1	n.d.	0.1
	3	29.0	38.2	24.6	6.8	1.1	0.1	0.2
	4	29.9	39.1	26.4	3.1	1.4	n.d.	0.1
	5	27.2	36.5	27.4	7.7	0.9	0.1	0.2
	6	29.7	38.7	24.1	5.6	1.4	0.1	0.4
	7	29.8	37.3	22.6	7.8	2.1	n.d.	0.4
	8	29.9	36.2	27.0	5.5	1.2	0.1	0.1
	9	27.6	40.3	23.4	7.3	1.2	0.1	0.1
	10	26.2	41.1	25.9	5.4	1.0	0.1	0.3
	11	27.1	38.4	29.0	5.4	1.7	n.d.	0.4
	12	27.9	41.4	23.1	5.6	1.7	0.1	0.2
	13	31.9	37.2	22.6	6.7	1.1	n.d.	0.5
	14	29.0	38.9	24.5	4.8	2.3	0.1	0.4
Average		28.8	38.4	25.2	5.8	1.4	0.0x	0.3
Fernald Neck	1	29.6	32.4	27.0	3.6	6.6	0.2	0.6
Swanville	1	26.0	36.0	29.4	7.6	0.4	0.4	0.2
	2	24.9	35.1	32.3	6.3	0.9	0.4	0.1
	3	26.3	37.1	30.4	5.9	0.1	0.2	n.d.
	4	24.9	35.0	34.2	4.9	0.4	0.6	n.d.
Average		25.5	35.8	31.6	6.2	0.4	0.4	0.1
Clark Island	1	38.2	24.0	26.9	4.4	6.1	n.d.	0.4
	2	34.6	25.4	28.0	5.0	6.4	0.2	0.4
	3	29.8	28.5	30.5	5.8	4.7	0.3	0.4
	4	30.7	33.7	26.6	4.2	2.7	0.7	1.4
	5	36.5	19.8	25.1	12.1	4.8	0.3	1.4
	6	30.2	21.8	31.5	10.9	3.2	0.4	2.0
	7	35.0	29.1	25.4	6.1	3.4	0.7	0.3
	8	34.1	26.0	27.8	7.3	4.5	0.3	
	9	34.6	27.5	27.7	6.1	3.6	0.5	
	10	33.2	22.1	25.0	13.7	4.8	1.2	
	11	31.6	25.9	31.5	8.1	1.9	0.3	0.7
	12	29.7	6.8	41.4	18.7	2.0	0.8	0.6
Average		33.2	24.2	29.0	8.5	4.0	0.4	0.8
Waldoboro	1	34.7	33.4	21.8	3.0	6.5	0.3	0.3
	2	32.1	28.5	28.5	4.4	6.5	n.d.	n.d.
Average		33.4	31.0	25.2	3.7	6.5	0.2	0.2
Vinalhaven	1	30.0	30.1	33.2	6.0	0.1	0.6	
	2	28.9	36.3	28.3	6.3	0.1	0.1	
Average		29.4	33.2	30.8	6.2	0.1	0.4	
North Sullivan	1	32.6	21.0	38.9	6.6	0.1	0.5	0.3
	2	31.6	21.2	41.8	5.2	n.d.	0.1	0.1
	3	33.3	20.3	39.5	6.0	0.3	0.5	0.1
	4	28.2	30.8	35.7	4.8	0.2	0.2	0.1
	5	33.7	25.9	36.6	3.2	0.3	0.3	n.d.
	6	32.8	24.1	37.6	4.9	0.3	0.3	n.d.
	7	34 1	13.2	45.5	6.1	0.3	0.5	0.3
	8	30 0	16.2	46.6	6.4	0.1	0.4	0.3

TABLE 19—*Continued*

Area	Specimen No.*	Quartz	Potash Feldspar	Plagioclase	Biotite	Muscovite	Opaque Accessories	Nonopaque Accessories
N. Sullivan (*cont.*)	9	33.7	15.8	43.7	5.8	0.3	0.5	0.2
	10	33.3	23.7	36.8	5.9	0.1	0.1	0.1
Average		32.3	21.2	40.3	5.5	0.2	0.3	0.2
North Jay	1	32.8	28.7	29.3	3.0	5.9	0.3	
	2	30.9	33.9	25.8	4.2	5.2	n.d.	
	3	30.0	34.2	26.7	3.2	5.6	0.1	0.2
Average		31.2	32.3	27.3	3.5	5.6	0.2	
Hallowell	1	30.8	37.0	21.7	2.6	7.6	0.3	
	2	32.1	33.7	19.8	3.5	10.6	0.3	
	3	29.8	32.6	30.1	1.9	5.1	0.5	
	4	31.7	30.2	22.6	2.4	12.2	0.9	
	5	30.4	23.5	34.8	2.1	8.7	0.5	
Average		31.0	31.4	25.8	2.5	8.8	0.5	

seems to have been in abundant supply during all geological time, save possibly the Tertiary, and that in many petrographic problems we need concern ourselves as little about the origin of granite magma as we do about that of basaltic.

On the grounds of convenience alone there is much to be said for a pregeologic separation of granitic material, as has been most recently advocated by Buddington (1948); it is rather difficult to have to remelt this substratum every time we need granite magma, but, on the whole, it would probably be easier to do this than to explain how layers of granitic and basaltic liquid could remain unmixed for such vast stretches of time. We are under no compulsion to assume that this substratum is uniform in composition throughout, either vertically or laterally, or even that its composition varies systematically. Magmas tapped from different levels or localities might thus have the same *general* compositional properties but differ significantly in minor—and sometimes even in rather important—details, as appears to be the case with the New England calcalkaline granites. Without abandoning this very convenient source of intergranite differences, we may nevertheless suggest that assimilation is, or could be, partly responsible for them, though even to convert this suggestion into a barely tenable hypothesis would require much more information about the modal composition of New England metamorphic rocks than is likely to be available for a long time. Not the least obliging part of the whole hypothesis is that the mechanism by which a granitic substratum formed in pregeologic times is neither the business nor the responsibility of geologists; for us it is simply a part of the Creation, and we can wait for the astronomers and cosmogonists to unravel its history. If we cannot understand the explanation when it arrives, we may plead our ignorance of higher mathematics and let it go at that. The only risk we run—and it seems rather remote—is general agreement among students of the subject that no such

granitic substratum could have formed in pregeologic time.

Dr. Bucher (1950) has recently attacked this venerable hypothesis, urging that, as granites occur only in continents, they must have been formed from sediments. Many geologists, however, have pointed out that, so far as anyone knows, granites are indispensable for the formation of sediments. The argument here rapidly passes beyond the bounds of geological inquiry. It is worth suggesting, however, that the absence of the granitic layer under the oceans—the highlight of Bucher's discussion—would constitute a critical objection only to hypotheses which assert its presence there. The primordial substratum might be of enormous dimensions, more than ample to meet the petrographer's requirements, without even remotely approaching the magnitude of a continuous earth shell. Perhaps, to stand Bucher's argument on its head, that is why not only the continents but the continental sediments are where they are.

However this may be and notwithstanding its many advantages, few petrologists have made much use of the granitic substratum. Perhaps because we have been forced to put basaltic magma beyond the pale, most of us prefer to view the formation of granitic magma as a geological phenomenon, occurring during what we regard as geologic time, and probably in portions of the crust now exposed to observation. Examination of table 19 and of the various diagrams indicates that from a study of the composition of granite itself we can discover very little about the origin of granite magma. Carrying the argument of the preceding section to its logical conclusion and ignoring minor constituents, the initial composition of any one of the granite magmas in question would lie somewhere between the minimum in the thermal valley and the point farthest outside the valley. All the initial compositions would be fairly close together, and probably most of them would lie in the valley; none would be very far outside, even with the boundaries as outlined for the anhydrous system.

There seem to be only four known processes by which liquids of this composition might be formed, namely, remelting of older granites, immiscible separation of granitic magma from basaltic (or dioritic), crystal fractionation of basalt (or diorite), and selective refusion of metamorphic rocks. Except as it leads us back to a granitic substratum, pure remelting of an earlier granite accomplishes very little; if we deny the validity of the substratum hypothesis, this "explanation" is really a *petitio principii*, for it assumes the existence of granite prior to the existence of granite magma. We may be able to account for the origin of some particular granite magma in this fashion, but, when we get as far as the most recent unmelted earlier granite, we are right back where we started.

Under conditions so far obtained in the laboratory or reasonably inferred for the lithosphere during geological time, the possibility of a large-scale immiscible separation of granitic liquid from basaltic or dioritic seems very remote. We cannot, of course, exclude the possibility that in pregeologic time, under conditions we have no way of specifying, such a separation might have occurred and that it might then have taken place on a gigantic scale. This hypothesis, like the previous one, seems at first to offer the possibility of a geological origin of granite magma, but its most reasonable form is just another version of the "pregeological" or "primordial" explanations.

This virtually compels us to derive

granitic magmas either from crystal fractionation or from selective refusion, and it is intriguing to find that the major difficulties confronting both hypotheses are the same. To yield granites having the compositional properties described above, we evidently require large quantities of liquids of granitic composition. Each of these liquids must be sharply and completely separated from the material out of which it has been formed, whatever this may be, *before its own crystallization* begins. This separation of the granite magma from its parent apparently occurs at a time when, save for its volatile content or accidental accretion of heat from external sources, the magma's ability to make room for itself by chemical interaction with country rock is very limited. The preparation of reservoirs for granite magmas formed in either fashion would appear to be largely a tectonic affair, and no easier one way than the other.

TABLE 20*

IDENTIFICATION OF SPECIMENS

Westerly, Rhode Island:
1. Chapman quarry, gray
2. Chapman quarry, flesh
3. Smith North, main opening
4. Smith North property, ¼ mile east-northeast of 3
5. Dixon quarry
6. Calder and Carnie, pink
7. Calder and Carnie, gray
8. Catto quarry
9. Present Smith quarry, light pink
10. Present Smith quarry, blue
11. Present Smith property, small abandoned opening near cutting works
12. Present Smith property, abandoned opening near sawing shed
13. Same block as 12, blue (contact).

Bradford, Rhode Island:
1. Sullivan granite "mine"
2. West end of first quarry east of 1 (Newall ?)
3. East end of Newall (?) quarry
4. Klondike quarry
5. Easternmost quarry of Sullivan group

Chelmsford, Massachusetts:
Both specimens from Fletcher quarry, North Chelmsford. 1, fine; 2, coarse.

Westwood, Massachusetts:
1. Road cut on U.S. Highway 128, 500 feet northwest of intersection with Mass. Highway 109, center of cut on northeast side of road
2. Same site, 20 feet southeast of 1
3. Westwood quarry, northwest side of Mass. Highway 109 at intersection with U.S. Highway 128, southeast wall of quarry
4. Same quarry as 3, northeast wall
5. Same quarry, southwest wall
6. Floor of quarry near center
7. Westwood town dump quarry

Milford, New Hampshire:
1. Betters quarry, Brookline
2. Betters No. 2 (?), a few hundred feet east of 1
3. Bates quarry, Brookline-Milford line
4. Carleton quarry, Milford
5. New Westerly quarry
6. Same as 5, small abandoned working
7. Pease quarry
8. Lovejoy quarry.
9. Kitteridge quarry
10. Old Tonella quarry
11. Young quarry
12. Southern quarry, Milford Granite Company
13. Northern quarry, Milford Granite Company

Concord, New Hampshire:
1. Blanchard quarries, south end
2. Same, center
3. Same, north end
4. Maxwell quarry
5. Anderson (Crowley ?) quarry
6. State Prison Farm quarry
7. Old Anderson quarry
8. Lapierre Brothers quarry

Fitzwilliam, New Hampshire:
1. Thompson quarry
2. Webb Hill, west quarry
3. Webb Hill, east quarry
4. Victoria White No. 3 quarry
5. Victoria White No. 1 quarry
6. Evans property, Three Derricks quarries, No. 1

* Few of the readers of this paper will have occasion to visit the areas covered, and it seems unwise to burden the table with detailed localities for each quarry. Each specimen is therefore located by the name of the quarry from which it was taken. Most of these quarry names were used by Dale (1923), and in almost every case he gives either good instructions for reaching them or excellent locality maps. The names are all familiar to local residents; visitors to any one of these areas will find older inhabitants eager to talk about the great days of the quarrying industry and more than willing to help in finding the quarries.

7. Same, No. 2
8. Same, No. 3
9. Angier quarry
10. North Pole quarry
11. Yon quarry
12. Perry quarry
13. Norcross quarry (Troy)
14. Webb quarry (Marlboro)

Woodbury, Vermont:

1. Woodbury Granite Corporation, lower quarry
2. Fletcher quarry
3. Webber quarry
4. J. B. Hall quarry
5. Imperial Blue quarry
6. Same as 5
7. Vermont White quarry
8. Drennan quarry

Barre, Vermont:†

1, 2, 3. Wells-Lamson quarry
4, 5, 6, 7. Wetmore Morse quarry
8, 9, 10. Smith Granite Company quarry
11, 12, 13, 14. J. K. Pirie Estate quarry
15, 16, 17, 18, 19, 20, 21, 22. Rock of Ages quarry; results for 22, a very fine-grained microporphyritic aplite, not included in the calculations.

Bethel, Vermont:

1. Ellis quarry, Christian Hill

Pownal, Maine:

1. Bow Street quarry, Freeport.
2. Same as 1
3. Hodson quarry, Pownal dark
4. Same as 3, light
5. Hodson upper quarry
6. Layton quarry, white
7. Layton quarry, dark
8. Bundy No. 1 quarry
9. Bundy No. 2 quarry (by roadside)
10. Abandoned opening about 700 feet south of 9
11. Outer Latti quarry
12. Main Latti Royall Road quarry
13. Hodson Road quarry just south of Royall Road
14. Main Latti Hodson Road quarry

Fernald Neck, Maine:

1. S. J. Hannaberry quarry

Swanville, Maine:

1, 2, 3, 4. From widely separated points in main quarry of Royal Quarry Company

Clark Island, Maine:

1. Bassick Brothers quarry, South Thomaston
2. Weskeag (Hudson) quarry, South Thomaston
3. Jo's Station Motion, South Thomaston
4. Jameson Motion, South Thomaston
5. Eagle quarry, Harrington Cove
6. Long Cove quarry, St. George
7. Wildcat quarry, St. George
8. Clark Island quarry
9. Same as 8
10. J. Meehan quarry, Clark Island Post Office
11. St. George (Smalley) quarry, St. George
12. Road cut, granite with gabbro breccia fragments, 2.7 miles north of St. George Granite Company

Waldoboro, Maine:

1. Quarry 0.7 mile west of railroad station
2. Quarry on west side of U.S. Highway 1, 0.3 mile north of Jefferson Street

Vinalhaven, Maine:

1. Pequoit quarry
2. Duschesne quarry

North Sullivan, Maine:

1. Havey-Robertson quarries
2. Same as 1
3. Abbot quarry
4. Porcupine quarry
5. West quarry
6. Crabtree-Havey quarry
7. Havey (Heatle ?) quarry
8. Blaisdell quarry
9. First opening east of 8
10. Coombs quarry, Franklin

North Jay, Maine:

1. American Granite Company quarry
2. Maine and New Hampshire Granite Company quarry
3. Same as 2

Hallowell, Maine:

1. Perry quarry
2. Gipson quarry
3. Minor quarry
4. Jim Bailey quarry
5. Lithgow Hill Motion

† For more specific locations of specimens in each quarry see Chayes (1950a).

From a knowledge of the composition of granite we cannot choose between the hypotheses of crystal fractionation and selective refusion, nor can we be of much assistance to the structural geologist in his search for a reasonable tectonic process for generating magma chambers. As for the first of these matters, it is certain-

ly a fair guess that much elucidation would result from careful and extensive work on the quantitative modal composition of the common sediments and metamorphic rocks.

Finally, it is neither necessary nor permissible to argue that *all* rocks now called "granites" are formed from granite magmas. There is, nevertheless, a vast quantity of granite which does seem to be of this origin, and it is up to the structural and regional geologist to find some method of introducing the requisite amount of magma into the upper levels of the crust, holding it there for considerable periods of time as a liquid, and permitting it to crystallize with little interference from the confining rock. Theorists may regard this as inconvenient or impossible, but anyone who cares to study granites closely enough will soon realize that it is necessary.

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MULTIPLE EMPLACEMENT OF THE IDAHO BATHOLITH[1]

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ABSTRACT

Evidence has been found that casts doubt on the long-held view that the Idaho batholith was emplaced essentially as a unit. This evidence indicates that the batholith is composed of discrete masses of granitic rock, some of which came to place under deep-seated conditions, others at much shallower depths. The deeply seated emplacements include two closely related, but separately formed, masses; the earlier evolved while deformative stresses associated with a major orogeny were still quite intense, the other evolved during the later, less intense stages. These masses probably had their roots in the same source. The granitic bodies introduced under less deep-seated conditions came from a younger, probably unrelated source.

The older rocks of the batholith resemble and are tentatively correlated with the granitic rocks of Oregon and Washington, which were emplaced at the close of the Sierra Nevadan orogeny, hence near the end of Jurassic time. The younger rocks appear to be associated with Laramide structures and are believed to be a product of the Laramide orogeny of late Cretaceous time.

INTRODUCTION

That the Idaho batholith (fig. 1), with minor exceptions, came to place essentially as a unit is an opinion long held by most geologists who have examined parts of the huge body. This opinion has been ably presented by C. P. Ross (1936, p. 374), who has worked over more of the batholith and has given more attention to the problem than perhaps any other person. Ross (1936, pp. 373–375), as well as the writer (1930, pp. 17–24; 1947, pp. 130–134; Anderson and Rasor, 1934, pp. 287–294), however, recognized a time interval between the emplacement of an apparent border facies of gneissic quartz diorite and a great inner mass of quartz monzonite and noted that the rock along the margin of the batholith formed under more intense orogenic stress than did the somewhat later main mass of the batholith.

Possible exceptions to this concept have been recognized. Ross (1936, p. 374) pointed out the intrusive character of irregular bodies of quartz monzonite that cut the batholith in the southwestern part of the Casto Quadrangle (Ross, 1934, pp. 37–38), but he believes that the two rocks are related genetically and are not much different in age. The writer also has seen bodies of granodiorite that cut the main mass of the batholith in Boise Basin (1947, p. 138). These he believes to be related geneti-

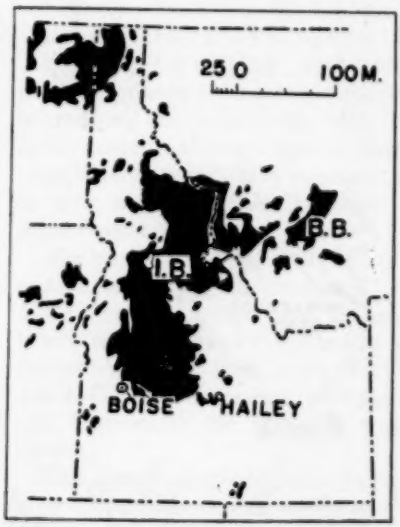

FIG. 1.—Map showing location of Idaho batholith (*I.B.*), Boulder batholith (*B.B.*), and other granitic bodies (*black*).

[1] Manuscript received January 11, 1951.

cally to masses of a distinctive type of pyroxene-hornblende-biotite diorite that intrude the batholith in Boise Basin (1947, pp. 134–137) and at Horseshoe Bend (1934, pp. 6–7), some miles to the west (fig. 2). For reasons cited in a succeeding section, this diorite is believed to be much younger than the main mass of the batholith. Then in the Hailey-Bellevue area (fig. 2), in apparent contradiction, the same type of diorite is found to be invaded by quartz monzonite of what had previously been thought to be a part of the main batholith (Anderson, 1950, pp. 4–5). These contradictory relations of the diorite to the batholith make it necessary to review the concept of one episode of batholithic emplacement and to consider the possibility that granitic rock of more than one age is present.

Numerous bodies of porphyritic rock mostly concentrated in so-called "porphyry belts" intrude, but are much younger than, the granitic rocks that compose the batholith (Anderson, 1947, pp. 139–151). These younger intrusives, mostly of mid-Tertiary age, have no bearing on the problem and are not considered.

The writer will first review the occurrence and other pertinent data of each

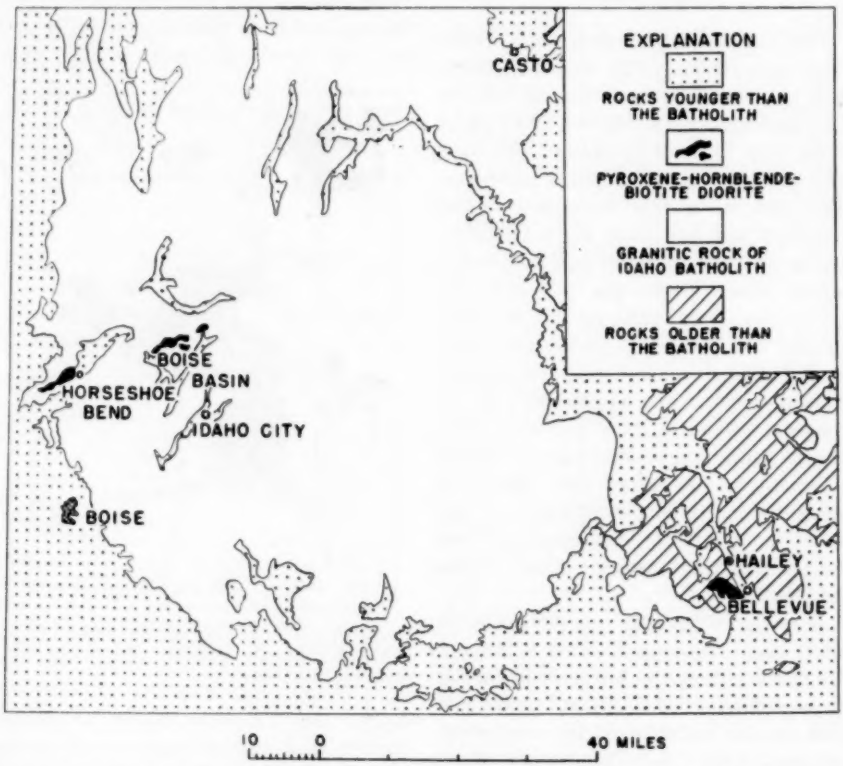

FIG. 2.—Map showing southern part of the Idaho batholith and bordering older and younger rocks (adapted from 1947 geologic map of Idaho).

of the involved rock masses and will then follow with his interpretations.

OLDER ROCKS OF THE BATHOLITH

MARGINAL FACIES

The so-called "marginal facies" is widespread along the western side of the batholith and has been traced through Horseshoe Bend (Anderson, 1934, pp. 4–6) into the western part of Boise Basin (Anderson, 1947, pp. 130–131) and thence northward into the northern part of the state (Anderson, 1930, pp. 17–20). It forms a broad but somewhat irregular border, as well as scattered roof masses in more central areas (Anderson, 1939, pp. 6–7), and is rather sharply delineated from the inner rock of the batholith by somewhat darker color and generally more or less conspicuous gneissic texture.

Much of the rock has the composition of quartz diorite; but some parts, because of endomorphic changes (Anderson, 1942, pp. 1103–1110), are more alkalic and silicic and have the composition of granodiorite and, exceptionally, quartz monzonite (Anderson, 1934, p. 5). Whatever its composition, the rock is moderately coarse-grained, gneissic, and contains a distinctive mineral assemblage that includes andesine, hornblende, and, generally, conspicuous grains of sphene and epidote, each of which may comprise up to several per cent of the rock. The other, nondistinctive minerals are quartz, variable but generally small amounts of microcline, and such accessory minerals as zircon, magnetite, apatite, allanite, and locally muscovite.

The facies is cut by associated pegmatite dikes, which indicate complete crystallization of the border diorite before the inner quartz monzonitic body was emplaced. The gneissic structure of the quartz diorite indicates emplacement during an orogeny.

INNER FACIES

The inner facies cuts the marginal rock. This relation has been noted in various places (Anderson, 1930, pp. 18–20; Ross, 1936, p. 374; Anderson, 1947, pp. 130–131). In some the contact is rather ill defined, but in others it is sharp and locally accentuated by apophyses that penetrate the marginal rock.

The rock of the inner facies is largely a quartz monzonite with transitions into granodiorite and locally into granite. Most of the rock is moderately coarse-grained but lacks the gneissic structure, the hornblende, and the conspicuous grains of sphene and epidote that distinguish the marginal rock. It also contains oligoclase rather than andesine as its distinctive plagioclase. Because it has one-third to one-half as much biotite as the marginal rock and also a general lack of hornblende, it is lighter colored. Other minerals present are quartz, orthoclase, microcline, and muscovite, with negligible amounts of zircon, apatite, garnet, magnetite, allanite, locally monazite, and in some places very small amounts of sphene and hornblende.

The inner facies is also cut by aplitic quartz monzonite (Anderson, 1947, pp. 132–133) of somewhat finer grain and locally by many dikes of aplite and pegmatite (Anderson, 1930, p. 22; 1947, pp. 133–134). Some of the associated pegmatite dikes enter the bordering quartz diorite.

This facies apparently was emplaced after the orogenic forces, which affected the marginal rock, had largely died away. Like the earlier rock, it appears to have formed under rather deep-seated conditions. The sharp contact and penetrating apophyses suggest that a structural break of some magnitude intervened between the consolidation of the quartz diorite and the emplacement of the

quartz monzonite (Anderson, 1947, p. 130).

PYROXENE-HORNBLENDE-BIOTITE DIORITE

As pointed out in the introduction, masses of a distinctive type of pyroxene-hornblende-biotite diorite have a significant role in the problem of the multiple emplacement of the batholith. Because the diorite intrudes the batholith at Horseshoe Bend (Anderson, 1934, pp. 6–7) and in Boise Basin (Anderson, 1947, pp. 134–137) and is intruded by the batholith in the Hailey-Bellevue area (Anderson, 1950, p. 4), it serves to effect a natural separation of the granitic rocks of the batholith into the complex of older rocks just described and a younger complex yet to be described. As the diorite in these localities is identical in appearance, composition, and petrographic details and is unlike any other diorite in Idaho, it appears to be well suited to its role as a time-marker. Its prevailing composition is that of a calcic diorite, near gabbro, and it bears a petrographic and petrologic stamp that is easily recognized in the field and the laboratory.

DIORITE AT HORSESHOE BEND

At Horseshoe Bend (Anderson, 1934, pp. 6–7) the pyroxene-hornblende-biotite diorite is intruded along a complex zone of structural weakness that cuts the marginal quartz diorite of the batholith. It forms a stocklike body about 8 miles long and up to $1\frac{1}{4}$ miles wide, elongated in an east-northeast direction (fig. 2).

The rock that composes the stock is fine-grained and nearly black at chilled margins but otherwise is prevailingly dark gray and medium-grained, with individual minerals about 2 mm. in diameter. In much of the rock the biotite forms rather conspicuous grains, a feature which seems to be characteristic of the rock wherever it occurs.

The rock shows some minor variations in composition, but it is chiefly a quartz-bearing hypersthene-augite-hornblende-biotite diorite, with accessory sphene, zircon, apatite, allanite, magnetite, and orthoclase. Few of these minerals, except the biotite, can be positively identified in hand specimens. The biotite tends to form rather large grains, which give the rock somewhat of a porphyritic appearance, but thin sections reveal that the "phenocrysts" are made up of clusters of small grains, all with the same orientation. The dark minerals comprise from 20 to 45 per cent of the rock, normally about 30 per cent, with hypersthene forming 2–20 per cent, augite 2–15 per cent, and hornblende and biotite each 5–15 per cent. Of the light-colored minerals, calcic andesine forms 60–70 per cent of the rock, quartz up to 4 per cent, and orthoclase up to 2 per cent. The content of quartz and orthoclase appears to increase with that of biotite.

The minerals display marked reaction phenomena. The plagioclase is highly zoned and has cores as calcic as labradorite and rims as sodic as oligoclase. The dark minerals show extensive mantling, the pyroxenes by hornblende and biotite and the hornblende by biotite. In places the quartz and orthoclase form patches of micropegmatite. The zoned feldspars and mantles suggest incomplete reaction between the early crystals and the liquid and are therefore evidence of rather rapid cooling during crystallization.

DIORITE IN BOISE BASIN

In Boise Basin (Anderson, 1947, pp. 135–136), which is about 12 miles east of Horseshoe Bend (fig. 2), the bodies of pyroxene-hornblende-biotite diorite, of which there are several, intrude the

quartz monzonite and granodiorite of the inner part of the batholith. The largest body forms a stocklike mass 11½ miles long and up to 1½ miles wide, elongated in an east-northeast direction along a zone of structural weakness similar to, and arranged en echelon with, the one at Horseshoe Bend.

As at Horseshoe Bend, most of the rock is moderately dark gray and medium-grained with average grains ranging from 2 to 3 mm., but the marginal rock is dark gray to black and has grains 1 mm. or less in diameter. It also has clusters of biotite grains, which tend to give the rock a somewhat porphyritic appearance.

The rock is identical with that at Horseshoe Bend and is mostly a quartz-bearing hypersthene-augite-hornblende-biotite diorite, with minor amounts of orthoclase and accessory sphene, apatite, magnetite, allanite, and zircon. The hornblende and biotite are commonly the most abundant of the darker minerals, the hornblende content ranging from 8 to 30 per cent (average 15 per cent) and the biotite from 5 to 10 per cent. Augite commonly amounts to no more than 5 per cent of the rock (exceptionally 20 per cent) and hypersthene less than 12 per cent. The plagioclase content ordinarily ranges from 65 to 70 per cent, and orthoclase and quartz each less than 5 per cent.

The minerals show striking zonal and mantling relations. The plagioclase commonly has labradorite cores and oligoclase rims, and the dark minerals are mantled like those at Horseshoe Bend. In places the quartz and orthoclase form micropegmatitic intergrowths. The reaction phenomena suggest rather rapid cooling of the magma and hence consolidation at no very great depth.

DIORITE IN THE HAILEY-BELLEVUE AREA

In the Hailey-Bellevue area along the eastern margin of the batholith (fig. 2) the pyroxene-hornblende-biotite diorite forms a body about 5 miles long and 2½ miles wide, elongated in a northwesterly direction and conforming closely with the structural trend of the much faulted Milligen and Wood River formations (Mississippian and Pennsylvanian). The body has a sill-like relationship and conforms roughly with the northwesterly strike and southwesterly dip of the intruded Milligen formation, with the dip of the underside ranging from 30° SW. to 50° SW. On the west the body is cut off and at depth is underlain by quartz monzonite belonging to the younger batholithic complex.

As at Horseshoe Bend and Boise Basin, the diorite is remarkably uniform and shows but little variation in appearance and composition. Most of the rock is moderately dark gray, medium-grained, and distinguished by rather conspicuous grains of biotite.

The rock is also classed as a quartz-bearing hypersthene-augite-hornblende-biotite diorite, with zoned plagioclase and minor or accessory amounts of sphene, zircon, apatite, allanite, magnetite, and orthoclase (Anderson, 1950, p. 4). Zoned plagioclase (andesine-labradorite) composes all but about 30 per cent of the rock; biotite, about 10 per cent; hypersthene, augite, and hornblende collectively about 15 per cent; and quartz and orthoclase ordinarily each less than 5 per cent. The hypersthene, augite, and hornblende are present in variable amounts, with the hypersthene locally more abundant in marginal parts of the body than the other dark minerals.

The minerals show the striking mantling or reaction relationships that char-

acterize the rock at Horseshoe Bend and Boise Basin. Megascopically and microscopically the rock is indistinguishable from the rock at these two localities.

YOUNGER ROCKS OF THE BATHOLITH

GRANODIORITE OF BOISE BASIN

Several bodies of granodiorite that invade the batholith in Boise Basin are exposed several miles south of Idaho City or some 13 miles south of the bodies of pyroxene-hornblende-biotite diorite (fig. 2). The largest of these bodies occupies several square miles within the inner part of the batholith.

These younger bodies of granodiorite are appreciably finer-grained than the rock they intrude, particularly at or close to marginal areas; but the difference in grain size—medium as compared to moderately coarse—may be easily overlooked, especially in the inner parts of the larger masses. The rock of these bodies is somewhat darker than the invaded rock because of a larger proportion of ferromagnesian minerals. These minerals comprise 8–12 per cent of the rock and are about equally divided between biotite and hornblende. The other minerals are zoned andesine (about 55 per cent), orthoclase and microcline (10–15 per cent), quartz (20–25 per cent), and such accessory minerals as sphene, epidote, apatite, zircon, allanite, and magnetite.

The hornblende, biotite, and plagioclase exhibit reaction phenomena and thus indicate that they formed under conditions of rather rapid cooling.

QUARTZ MONZONITE IN THE HAILEY-BELLEVUE AREA

In the Hailey-Bellevue area (fig. 2) the quartz monzonite has been emplaced under and along the southwest side of the pyroxene-hornblende-biotite diorite and with the largest exposure measuring about 4 miles in length and 1–1½ miles in width (Anderson, 1950, p. 4). It is separated from a much larger mass to the west by a roof pendant of Carboniferous strata and may be traced almost without interruption into the granitic rocks of the Hailey gold belt, some 10 miles west of Bellevue (Anderson and Wagner, 1946, p. 5), and from there, with little break, into the main body of the Idaho batholith, a few miles to the northwest. Altogether, this young quartz monzonite appears to underlie many square miles and may constitute a batholith in its own right.

In places small stocklike bodies of the quartz monzonite penetrate the diorite, but in general the contact between the quartz monzonite body and the pyroxene-hornblende-biotite diorite is rather even. Because of the marked difference in color between the two rocks, the boundary separating them is easy to trace, particularly where the bordering diorite has been somewhat sheared and further darkened by secondary products formed by contact alteration. In the southern part of the area, the contact is nearly horizontal, with inclination to the east at an angle of about 10°. In the northwestern part of the area the dip becomes progressively steeper, reaching a maximum of 70°.

Most of the rock is about as coarse-grained as the rock that composes the main mass of the Idaho batholith, and some of it is as conspicuously porphyritic, with microcline phenocrysts locally measuring 1 inch or more in length. Near the diorite the rock is somewhat darker than the main mass of the batholith but becomes lighter colored on approaching the Hailey gold belt.

The quartz monzonite shows marked mineralogic resemblance to the grano-

diorite in Boise Basin and, like that in the basin, contains andesine, microcline, quartz, biotite, and hornblende as the more abundant minerals, and such minerals as sphene, zircon, apatite, allanite, magnetite, ilmenite, and epidote as accessories (Anderson and Wagner, 1946, p. 5; Anderson, 1950). Andesine and microcline are about equally abundant; quartz ranges from 20 to 35 per cent; biotite, 5–10 per cent; and sphene and hornblende up to several per cent each. The presence of hornblende, rather abundant sphene, and andesine seems to characterize all the younger granitic rocks of the batholith.

The quartz monzonite locally is accompanied by a host of aplitic and pegmatitic dikes, with a swarm also extending into the adjacent pyroxene-hornblende-biotite diorite (Anderson, 1950, p. 5).

QUARTZ MONZONITE OF THE CASTO QUADRANGLE

The irregular masses of granitic rock that cut the Idaho batholith in the west-central and southwestern parts of the Casto Quadrangle (fig. 2) have the composition of quartz monzonite. As pointed out by Ross (1935, p. 37), the rock is somewhat finer-grained and characteristically more nearly white than the typical quartz monzonite of the Idaho batholith and somewhat more silicic and potassic. Ross supplies no mineralogic details but states that the white quartz monzonite is similar in composition to the typical rock of the batholith, which locally consists of quartz, potash feldspar (mainly microcline), oligoclase-andesine, biotite, small amounts of muscovite and hornblende, and minor amounts of apatite, sphene, and magnetite.

Because the similarity between the white quartz monzonite and that described as typical of the Idaho batholith in the region is so great, both in composition and in degree of alteration, Ross suggests that the two are related genetically. One must, however, consider an alternative interpretation—that the rock, though similar in composition to the invaded rock, may have been emplaced much later, perhaps at the same time as the young granodiorite in Boise Basin and the also young quartz monzonite in the Hailey-Bellevue area. The finer grain of the irregular intrusive bodies in the Casto Quadrangle suggests intrusion into rather cold rocks and hence not during the general interval when the main batholith was being emplaced.

From the descriptions of many of the rocks that compose the batholith in other areas, it seems likely that many bodies of granitic rock with petrographic resemblance to the younger granitic rocks in Boise Basin and the Hailey-Bellevue area may belong to the group younger than the pyroxene-hornblende-biotite diorite.

CORRELATION AND AGE

OLDER ROCKS OF THE BATHOLITH

Ross (1936, pp. 382–383) has pointed out the similarity of the rocks of the Idaho batholith to the older intrusives in Oregon and British Columbia and has concluded that the batholith was intruded about the same time as the granitic rocks of the Sierra Nevada and other areas nearer the Pacific Coast. The writer (1934, pp. 5–6) has also noted the striking similarity in composition and mineralogy of the batholithic rock in the Horseshoe Bend area to the granitic rocks of Oregon and Washington, which are likewise characterized by rather calcic compositions and high titanium contents (Waters, 1933, p. 261). This correlation with the rocks to the west seems applicable to all the rocks of the

batholith known to be older than the bodies of pyroxene-hornblende-biotite diorite.

In Washington and Oregon, Waters (1933, pp. 258–262) noted that the principal period of deformation and batholith intrusion was at about the end of the Jurassic and could not have been later than early Cretaceous, inasmuch as Cretaceous beds rest in angular unconformity on the deformed Jurassic and older rocks. From a critical consideration of the available data, Ross (1928, pp. 673–693; 1936, pp. 382–383) concluded that the Idaho batholith was emplaced at or near the close of the Sierra Nevadan orogeny. The writer shares in this view with respect to the older rocks of the batholith.

PYROXENE-HORNBLENDE-BIOTITE DIORITE

If the marked reaction phenomena exhibited by the pyroxene-hornblende-biotite diorite may be taken as evidence of rapid cooling, the dioritic magma must have been intruded into cold rock and at a level much closer to the surface than the level of emplacement of the batholithic host. Thus much of the cover must have been stripped from the batholith before the diorite, which has hypabyssal characteristics, was intruded. The time of the intrusion, however, can be reckoned locally only from structural relationships. Elsewhere the writer (1947, pp. 134–135; 1948, pp. 90–92) has pointed out that the dioritic bodies in Boise Basin and Horseshoe Bend were intruded along zones of structural weakness believed to have been formed during the Laramide orogeny, when the orogenic forces were transmitted nonuniformly through the batholith against the thick accumulation of sedimentary materials in the Laramide trough, then being deformed. It is believed that the fracturing along east-northeast shear zones localized and facilitated intrusion of magma during the later stages of the orogeny.

The pyroxene-hornblende-biotite diorite cannot, so far as is known, be correlated with any other diorite in Idaho. It may, however, be similar to some of the dioritic bodies associated with the Boulder batholith in Montana (Pardee and Schrader, 1935, pp. 4–5, 17–18) and with some of the satellites of the batholith in the Philipsburg (Emmons and Calkins, 1913, pp. 88–96) and Helena (Clapp, 1932, p. 27) areas. Although the writer has not seen the rocks in these areas, those that contain hypersthene, augite, hornblende, biotite, and zoned plagioclase (Emmons and Calkins, 1913, pp. 88–91) seem very much like the Idaho rocks. The Montana diorite appears to be older than, but related to, the Boulder batholith, intrudes strata as young as Cretaceous, and is regarded as having come into existence during the later stages of the Laramide orogeny, near the end of Cretaceous time. If the Idaho and Montana diorites can be correlated, as seems likely, then the writer's earlier assignment of the diorite to the Laramide on structural grounds seems to be substantiated.

YOUNGER GRANODIORITE AND QUARTZ MONZONITE

As the younger granodiorite in Boise Basin exhibits reaction phenomena indicative of fairly rapid cooling, it, like the pyroxene-hornblende-biotite diorite, must have invaded cold batholithic rock relatively close to the surface, probably not long after the intrusion of the diorite (Anderson, 1947, p. 138). In the Hailey-Bellevue area, Hewett (1930, p. 213), who noted the similarities in mineral composition and texture between the quartz monzonite and diorite, concluded that the two were derived from a

single magmatic source and that the shape of the surface of contact indicated that the diorite was still viscous when the granite (quartz monzonite) was intruded. The writer would modify this conclusion only to regard the diorite as crystalline when the quartz monzonite was emplaced and to postulate that sufficient time intervened before the quartz monzonite was emplaced to permit the necessary compositional changes at the magmatic source. From structural and genetic considerations it is concluded that the younger bodies of granodiorite and quartz monzonite should be linked to the same orogeny as the somewhat earlier but related diorite, that is, to the later stages of the Laramide orogeny near the close of the Cretaceous period.

The theory that the younger granitic rocks may be late Cretaceous may have support from an age determination made on pitchblende obtained some years ago by J. C. Reed (1938, p. 8) from a placer deposit in the Warren district in the north-central part of the batholith. It is presumed that the pitchblende came originally from a pegmatite. The lead-uranium plus thorium ratio indicated a late Cretaceous age. As the age of the batholith had been deduced as late Jurassic or early Cretaceous on other grounds, the findings based on the pitchblende study introduced a perplexing problem. However, if the pitchblende came from a pegmatite associated with the younger granitic rock, no problem exists; in fact, the pitchblende determination tends to support the existence of granitic rock of late Cretaceous age and hence the composite makeup of the batholith.

The younger granitic rocks of the batholith obviously were emplaced much closer to the surface than were the older rocks, although both now occur at the same level. In this respect the bodies of younger granitic rock resemble the Boulder batholith and its satellites, which are known to have consolidated at appreciably shallower depths than the older mass of the Idaho batholith. The writer has had the opportunity to cross the Boulder batholith a number of times and has had occasion to examine some of the rock from the Butte area in thin section. Rock so studied was indistinguishable from the young granodiorite in Boise Basin. From published descriptions (Weed, 1912, pp. 31–36; Pardee and Schrader, 1935, pp. 19–20) the rock of the Boulder batholith is largely a quartz monzonite of moderately coarse grain and, like the Idaho rock, is composed essentially of andesine, orthoclase, quartz, biotite, hornblende, locally a little augite, and variable but generally small amounts of such accessory minerals as sphene, allanite, zircon, magnetite, and apatite. Many of the satellitic bodies, like those in the Philipsburg area (Emmons and Calkins, 1913, pp. 91–113), have the composition of granodiorite and appear quite similar to the younger granodiorite and quartz monzonite in the Idaho batholith. From the structural and petrologic similarities it seems likely that the younger rocks of the Idaho batholith and the rock of the Boulder batholith are related.

SUMMARY AND CONCLUSIONS

The accumulating evidence suggests that the Idaho batholith is not essentially a unit mass but, on the contrary, is composed of discrete masses of granitic rock assignable to one or the other of two distinct age groups. Those of the older group consist of two closely related but separately emplaced masses, the earlier, which has generally been known

as the marginal or quartz diorite facies of the batholith, during the more active stages of a full-fledged orogeny; the later, which has generally been known as the inner or quartz monzonite facies, during the later, less intense stages of the same orogeny. Both are deep-seated emplacements with enough time intervening to permit each to evolve aplites and pegmatites.

Rocks of the younger group consist of an early intrusion of pyroxene-hornblende-biotite diorite and somewhat later emplacements of closely related granodiorite and quartz monzonite with associated aplites and pegmatites. These younger granitic rocks came to place at appreciably shallower depths than did the older rocks, apparently after considerable of the cover had been stripped from the earlier batholithic rocks. Thus part of the batholith is composed of rock that is truly deep-seated or abyssal and part of rock that is more nearly hypabyssal.

The older rocks of the batholith show resemblance to, and have been correlated with, the granitic rocks of Oregon and Washington and of the Coast Range and Sierra Nevada batholiths. As in the case of these rocks, the older rocks of the Idaho batholith are believed to have been emplaced during the later stages of the Sierra Nevada orogeny near the end of Jurassic time. The emplacement of the younger rocks of the batholith seems to be controlled in part by Laramide structures, and it is believed that their intrusion accompanied the closing stages of the Laramide orogeny. It is likely that these younger rocks are related and can be correlated with the rocks of the Boulder batholith and thus, like the rocks of the Boulder batholith, were emplaced near the end of Cretaceous time.

Distinguishing between the various components of the Idaho batholith is no simple matter. The fact that the presence of the younger rock of the batholith has so generally been overlooked indicates that the problem of resolving the batholith into its various parts is not going to be an easy one. Some results may be obtained from detailed petrographic studies, but such studies should be supplemented by age determinations of radioactive accessory minerals or of biotite by strontium or other methods.

From present knowledge the bulk of the batholith appears to be composed of the older (Sierra Nevadan) rocks; however, the younger rocks may be much more widely distributed and may constitute a much larger part of the batholith than is now realized. The combined efforts of many workers over a long period of time will be needed to complete the separation of the batholith into its component parts. It is hoped that this paper will direct attention to the composite nature of the batholith and provide the groundwork for others who may be interested in work on the problem.

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MENDOCINO SUBMARINE ESCARPMENT[1]

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ABSTRACT

A submarine scarp extends westward from Cape Mendocino, California, for at least 1,200 miles. Its height at 70 miles from shore is about 10,500 feet, and 1,000 miles from shore it is about 8,420 feet. The maximum average slope from top to bottom ranges from 7° to 10°; but portions of the scarp 1,000 feet high have slopes as great as 18°–24°. The scarp lies on the south side of a ridge which has a gentler slope toward the north in most places. Similar, but smaller, ridges and scarps are found to the north and south of the Mendocino Scarp and are parallel to it. Regional bathymetry shows that the sea floor for hundreds of miles south of the scarp is about ½ mile deeper than the sea floor for hundreds of miles north.

The scarp does not appear to be a seismically active submarine extension of the San Andreas fault, which passes out to sea at Cape Mendocino. Epicenters of submarine earthquakes trend northwest from Cape Mendocino rather than west along the Mendocino Scarp. The origin of the scarp is uncertain, but three hypotheses are considered. These suggest that it may be (1) a submerged "continental slope" between "continental" rocks to the north and oceanic rocks to the south, (2) a reverse fault, or (3) a strike-slip fault.

INTRODUCTION

THE "HORIZON" SURVEYS

At the suggestion of the writers, the homeward course of the Scripps vessel "Horizon" from Bikini Atoll to San Diego, California, was directed north of the shortest route in order to determine whether a great submarine scarp extends far to the west from Cape Mendocino, California. The reconnaissance of the scarp was the concluding part of the joint Scripps Institution of Oceanography and Navy Electronics Laboratory Expedition to the Mid-Pacific, 1950. The previously questionable existence of the scarp was verified by detailed sounding lines at four crossings with a spacing of 100–200 miles.

In August, 1951, the "Horizon" made a more detailed reconnaissance of the scarp as a part of "Operation Northern Holiday." Eighteen crossings of the scarp had an average spacing of about 50 miles, and a course was run along the scarp for about 100 miles in a search for submarine canyons.

In the present paper the topography along the Mendocino Scarp is described on the basis of the "Horizon" surveys and earlier soundings from all sources; a tectonic interpretation of the topography is also included.

PREVIOUS KNOWLEDGE

The first account of a part of the submarine topography off Cape Mendocino (Murray, 1939) was based on United States Coast and Geodetic Survey soundings and included a chart, with a contour interval of 100 fathoms, showing the bathymetry of the sea floor for a distance of about 70 miles from the shore. Shepard and Emery (1941) also used Coast and Geodetic Survey soundings to prepare a chart of about the same area with a contour interval of 50 fathoms. They noted, moreover, that "sporadic" soundings suggested that the scarp could be traced at least 400 miles west of the coast. More recently Colbert (1949) and Studds (1950) have referred briefly to the scarp in annual summaries of the results of Coast and Geodetic

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Survey work; new crossings of the inshore part of the scarp were made by Survey ships traveling to and from the Aleutian Islands. Colbert stated that ". . . an indication was obtained of a continuation of the submarine scarp off Cape Mendocino, California, to a point 300 miles seaward." Studds said: "The westward continuity of the submarine scarp off Cape Mendocino, California, was substantiated at a distance of 200 miles off the coast."

The Mendocino and Gorda scarps (Shepard and Emery, 1941) are unusual topographic features because of their combined great length, because they trend perpendicular to the "concordant" coast of the Pacific Ocean, and because few scarps of any kind are known to exist on the floors of the deep oceans. It is interesting to note, however, that a long submarine scarp trending perpendicular to the shore was discovered by Dietz (1952) on the United States Navy Antarctic Expedition of 1946–1947. This scarp extends along longitude 35° E. for at least 300 miles from Antarctica. It has an average slope of 44° and a height of 9,600 feet; the top is at 1,100 fathoms and the bottom at 2,700 fathoms. The Antarctic scarp also resembles the Mendocino and Gorda scarps, in that it lies on the steep side of an asymmetrical ridge.

NAME OF THE SCARP

No official name has been assigned to the great submarine scarp which is the subject of this paper. However, some name, even though unofficial, is required in order to avoid awkwardness and ambiguity. The choice of a name is complicated by matters which will now be outlined.

Shepard and Emery (1941) applied the name "Gorda Scarp" to the north-facing scarp, which extends 70 miles from shore (to the edge of their chart). The name was selected because the closest approach of the scarp to the shore is off Punta Gorda, a comparatively minor promontory 13 miles south of Cape Mendocino. At about 30 miles beyond the area shown in Shepard and Emery's chart the north-facing scarp becomes more subdued, but the westward topographic trend continues along a much higher south-facing scarp, which lies about 15 miles to the south. The south-facing scarp extends for at least 1,100 miles. This long south-facing scarp has not been named, unless it is considered to be an extension of the Gorda Scarp. The writers consider the two scarps to be separate, although they have the same trend and probably are parts of a "Mendocino trend" or "Mendocino structure." The south-facing scarp hereinafter is called the "Mendocino Scarp" because of its close relation to Cape Mendocino. At Cape Mendocino the regional trend of the coast changes from northwest to north, and the cape is a major promontory. As such, it is named on most charts and maps which show this area, even small-scale charts of the world. It seems suitable to name a great submarine scarp after a prominent geographical feature which is easy to locate.

The name "Mendocino Escarpment" or "Scarp" has also been applied to the near-shore, north-facing scarp which Shepard and Emery (1941) call the "Gorda Scarp." The first published mention of the scarp (Murray, 1939) refers to it as a "submarine scarp off Mendocino, California," without assigning a name. Smith (1941) called it the "Mendocino Escarpment," but in subsequent statements representatives of the Coast and Geodetic Survey have returned to

"submarine scarp off Cape Mendocino" (Colbert, 1949; Studds, 1950). The present writers, however, prefer to use "Gorda Scarp" for the inshore north-facing scarp, in order to differentiate it from the larger south-facing scarp.

SOURCES OF SOUNDINGS

Soundings used in constructing a bathymetric chart of the Mendocino Scarp are located on figure 1. Most soundings within 250 nautical miles of the coast were made by the "Horizon" and by ships of the U.S. Coast and Geodetic Survey. The contours within 70 miles of the shore are taken in part from Shepard and Emery (1941). The research ship "Carnegie" took one line of soundings about 250 miles from shore. Beyond 250 miles from the coast, the chief sources of soundings are the surveys by the "Horizon," and spot soundings by U.S. Navy ships, principally the "U.S.S. Ramapo." The "U.S.S. Burton Island" helped to correct a preliminary interpretation of the topography by making spot soundings in several critical unsounded areas. The 22-fathom sounding at 46°–45° N., 130°–147° W., was made during a survey by the U.S. Fish and Wildlife Service ship, "John Cobb."

CORRECTIONS IN SOUNDINGS

Most echo sounders are calibrated by assuming a sound velocity of 4,800 feet per second. However, the velocity of sound in the sea varies with temperature, salinity, and pressure, so that the assumed velocity is rarely correct, although the percentage error from this cause is small. For example, the "Carnegie" determinations of sound velocity (Fleming *et al.*, 1945) indicate that a correction of only 60 fathoms should be added to a sounding of 2,500 fathoms in the vicinity of the Mendocino Scarp. Hydrographic Office charts show uncorrected soundings because they are more useful than corrected ones for navigation. The contours figured in the present paper are based on uncorrected soundings.

Errors due to inaccurate positions, defective instruments, and faulty readings are more significant in the preparation of bathymetric charts than are errors due to uncorrected sound velocities. A rational bathymetric chart rarely can be drawn if all soundings are accepted as correct. A line of soundings which disagrees with other lines which it crosses may justifiably be rejected. Some sounding lines, clearly erroneous, were rejected in preparing the bathymetric charts; the positions of the rejected lines are shown in figure 1.

The writers have applied corrections for the variation of sound velocity with depth in computing the height and slope of the scarp from the "Horizon" soundings. Heights derived from corrected depths are expressed in feet in the text, and heights from uncorrected depths are expressed in nautical miles or in hundreds of feet. All distances are in nautical miles.

DESCRIPTION OF BATHYMETRY

REGIONAL BATHYMETRY OF THE NORTHEASTERN PACIFIC OCEAN

The submarine topography of the abyssal sea floor off the west coast of North America (fig. 2) may be separated into three distinct provinces. From Alaska south to about latitude 40° N., the sea floor is a rather smooth plain, sloping from the continent toward the west. A number of submarine volcanoes rise above the plain in the Gulf of Alaska. Many northeast-trending ridges and troughs have been found off Oregon and Washington. Far to the south, off

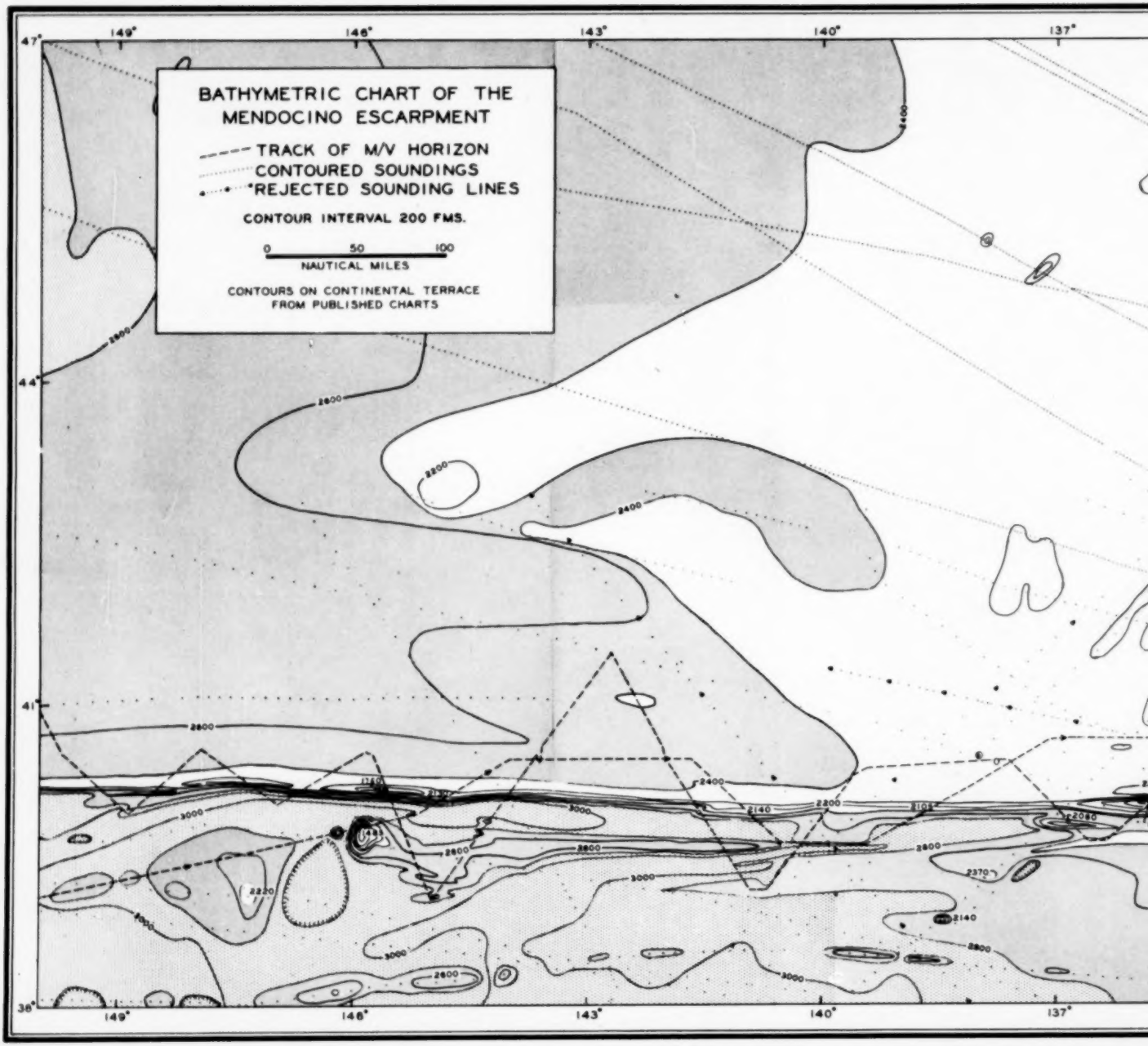
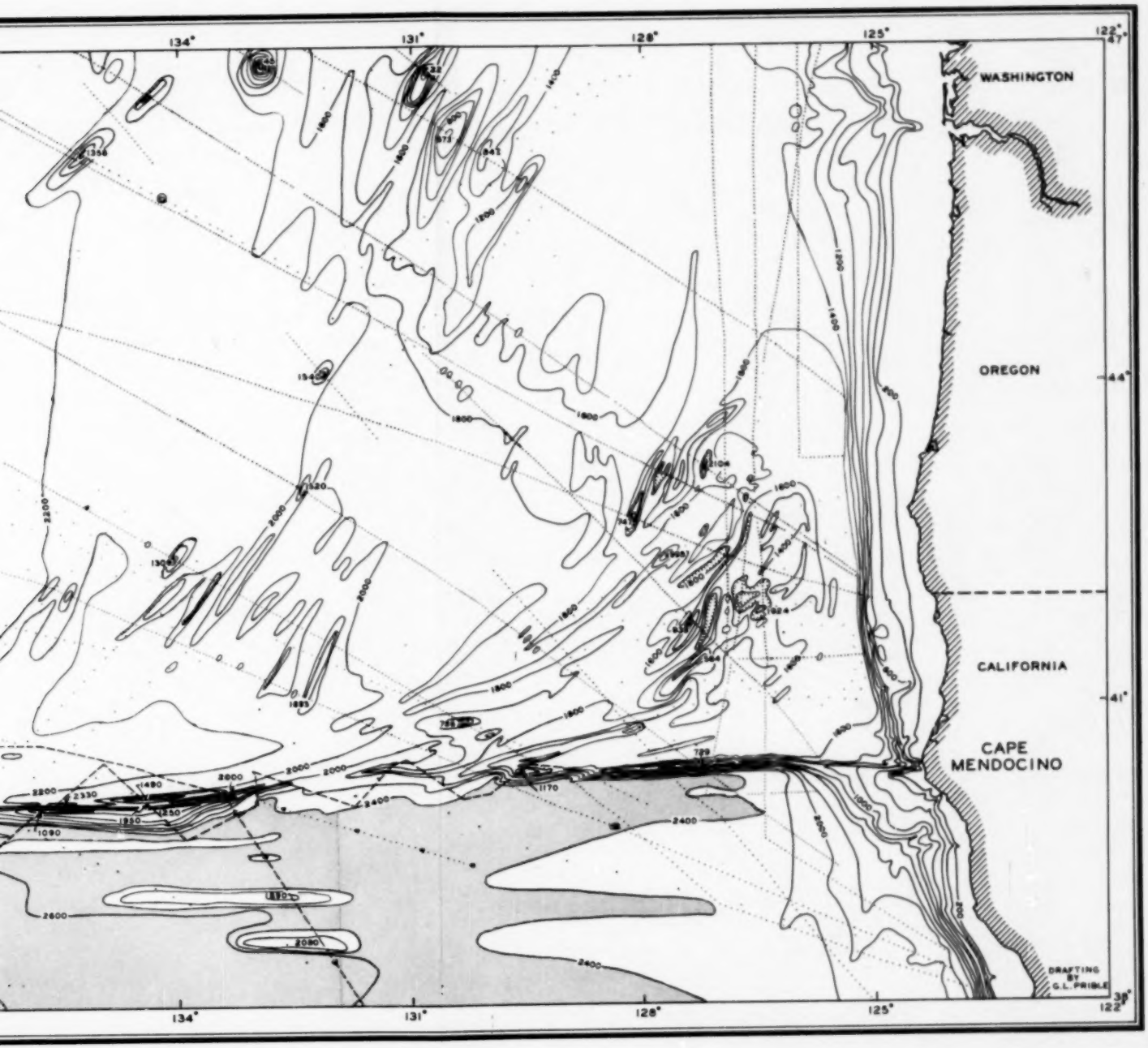


FIG. 1.—Bathymetric chart of the Mendocino



docino Escarpment. Contour interval 200 fathoms

Baja California, Mexico, is a mountainous rise, at a depth of about 2,200 fathoms, which is studded with submarine volcanoes. The rise is separated from the continent by a deep elongate trench parallel to the coast. Off central and southern California, between the "Alaskan plain" and the "Mexican rise," the sea floor is depressed about ½ mile, so that it is as deep as much of the central part of the Pacific Ocean. A long asymmetrical ridge—trending approximately perpendicular to the coast—lies between the "Alaskan plain" and the deep area off California. The ridge has a higher and steeper slope toward the deep to the south and a less steep slope toward the shallower floor to the north. The south side of the ridge is the Mendocino Scarp. The scarp is considered to

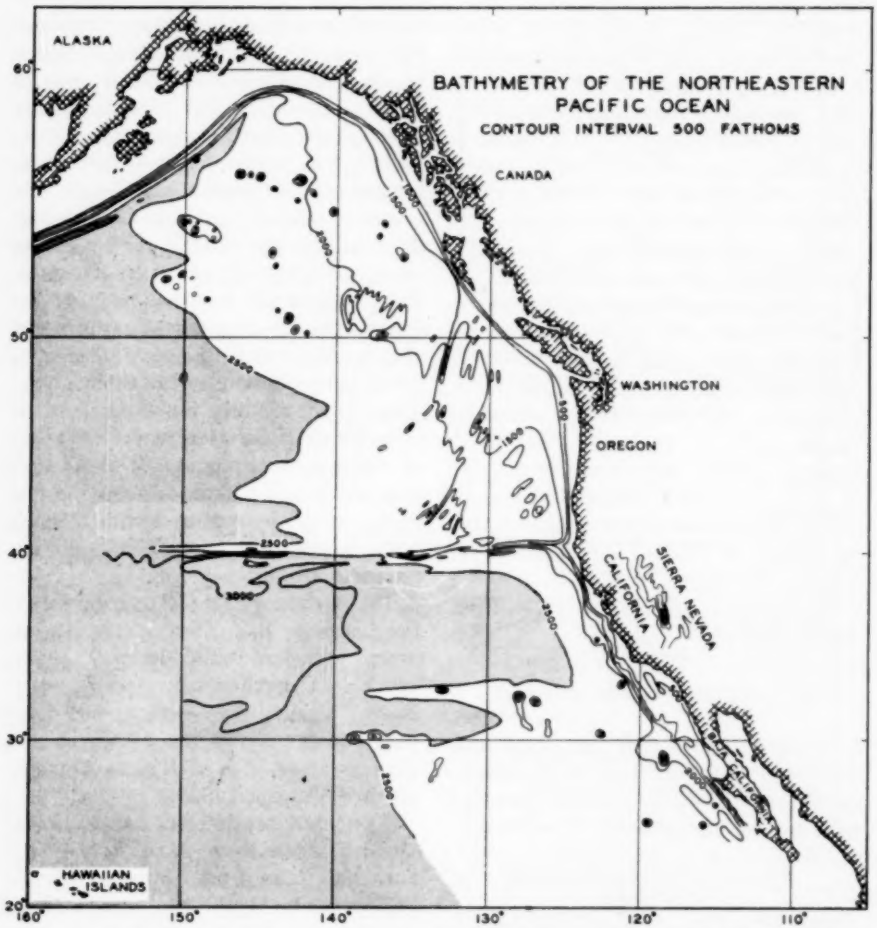


FIG. 2.—Bathymetric chart of the northeastern Pacific Ocean. Contour interval 500 fathoms (3,000 feet). The Sierra Nevada is contoured with the same interval for comparison with the Mendocino Scarp.

be more important than the ridge itself, because the region to the south of the ridge is about ½ mile deeper than the region to the north.

The Mexican rise and the deep area off California are likewise separated by an elongate, asymmetrical ridge, trending perpendicular to the coast. Available soundings suggest that the ridge may have a scarp, but this must remain questionable until the area is surveyed with modern equipment.

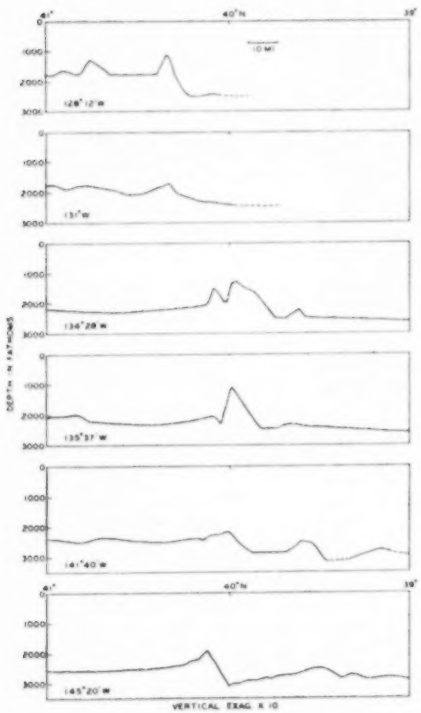


FIG. 3.—Profiles of the Mendocino Scarp

BATHYMETRY OF THE MENDOCINO SCARP AREA

The bathymetry of the Mendocino Scarp area is shown in figure 1. Profiles along west longitudes 128°12′, 131°, 134°28′, 135°37′, 141°40′, and 145°20′ appear in figure 3. Details of the bathymetry are self-evident but will be discussed briefly in order to emphasize certain features. It should be borne in mind that the sounding lines crossing the Mendocino Scarp are 10–70 miles apart and that between the lines the topography is unknown. Because of the wide spacing, all the contours might properly be dashed to indicate uncertain positions. However, the contours make sharp bends, and even with a contour interval of 200 fathoms (1,200 feet) they are bunched together in many places; so dashed lines would be very difficult to interpret. The writers have made the contours solid for ease of reading, but the positions of almost all the soundings used in making the chart are shown in figure 1, and the reader may judge for himself the accuracy of the positions of the contours and the possibilities of other interpretations of the bathymetry. The only sounding positions omitted from the chart are a few on the very tops of ridges and seamounts. It was found that the position dots or sounding-line dashes could be confused with contour lines where the lines are relatively crowded on steep slopes.

The portion of the Mendocino structure nearest the coast is the Gorda Scarp (Shepard and Emery, 1941), which is a north-facing, straight scarp about 75 miles long, with a maximum height of about 6,000 feet. The maximum slope is about 15°, and the average is about 3° (Kuenen, 1947).

The great south-facing scarp begins about 75 miles from shore. Between 75 and 200 miles from shore (longitude 126°05′ W. to 128°50′ W.), five crossings and one parallel line indicate a relatively simple, asymmetrical ridge, with

a much higher and slightly steeper scarp on the south side. The scarp has a maximum height of 10,500 feet and a maximum average slope from top to bottom of 8°–9°. The line of soundings along the crest of the scarp shows that the crest is irregular and suggests that the scarp may be dissected by submarine canyons, although the irregularities may have some other origin.

Six sounding lines show a very different type of scarp between 200 and 380 miles from shore (longitude 128°50′ W. to 132°45′ W.). The ridge and scarp are complicated by the intersection of a northeast-trending lineation which appears to be a continuation of the lineation of the ridges lying to the north. The maximum average slope is only a few degrees in most of this section. The maximum height is 8,400 feet, but it decreases to 3,300 feet in the western part, where the scarp has less relief than anywhere else along the 1,200 miles of its length which have been surveyed.

From 380 to 560 miles from shore (longitude 132°45′ W. to 136°40′ W.), the main scarp bends southwest for about 50 miles, where it takes a trend slightly north of west. The ridge is asymmetrical, but in this area it is steeper, although not so high, on the north side instead of on the south, as it is in all other areas of the scarp. A second, smaller ridge lies parallel to the main ridge on the north side. The two ridges are separated by a deep, narrow trench which has some local depressions. The maximum height of the scarp in this section is 8,580 feet, and the maximum average slope is 8°–9°. The north side of the main ridge has a maximum height of 7,560 feet, and an extraordinary maximum average slope of 28°. About 100 miles north of the main scarp are many northeast-trending ridges with an average height of 1,800 feet and an average width of 5–10 miles. Several ridges lie south of the main scarp and trend parallel to it. They are asymmetrical and rise abruptly from the otherwise flat sea floor. Locally these ridges have slopes of 25°–30°.

Twelve crossings by the "Horizon" and three spot sounding lines show a remarkably simple scarp from 560 to 1,200 miles from shore (longitude 136° 40′ W. to 150°00′ W.). The scarp has a maximum height of 8,420 feet, but along most of this section the height is about 5,000 feet. The maximum average slope is about 9°–10°; the "Horizon" fathograms, however, show how misleading average slopes may be. On two crossings, portions of the scarp, 1,000 feet high, were found to have slopes of 18°–24°. Paralleling the Mendocino Scarp to the south is an elongate, partly depressed deep, with a very flat floor about 10 miles wide. South of this deep is a wider, parallel, asymmetrical ridge which is steeper on the north side; it is about 2,500–3,000 feet high in most places, but one seamount rises 6,200 feet above the surrounding sea floor.

Returning from Kodiak to San Diego, the "Horizon" crossed a scarp at 39°06′ N., 154°30′ W., which drops from 2,390 fathoms to 3,000 fathoms in 3 miles. It is about 200 miles west and 60 miles south of the outermost known part of the Mendocino Scarp, but may be connected to it.

TECTONIC INTERPRETATION OF THE SUBMARINE TOPOGRAPHY

SEISMICITY OF THE MENDOCINO SCARP AREA

In a published discussion accompanying the first description of the scarp (Murray, 1939), N. H. Heck commented on the possibility that the Gorda Scarp marks an extension of the San Andreas

fault. Shepard and Emery (1941) also noted this possibility and discussed in detail the evidence for horizontal and for vertical movement. Earthquake epicenters, which accompany the San Andreas fault on land, extend out to sea at Cape Mendocino in a band with a trend to the northwest (fig. 4). Byerly (1937, 1938, 1940) has found that the distribution of the first motion of the submarine earthquake of July 6, 1934, "... combined with knowledge of the general faulting trends of the region, leads to the conclusion that the earthquake was caused by movement on a fault bearing about N 40° W, and dipping about 84° northeasterly." The Pacific side of the fault moved to the north relative to the continental side. The evidence of the strike and initial movement of one submarine fault and the general trend of a band of epicenters suggest that the San Andreas fault trends to the northwest from Cape Mendocino and does not bend to the west to follow the Mendocino Scarp. A number of depressions, which appear anomalous in relation to the surrounding northeast-trending ridges and troughs, lie in a narrow band with the same trend and position as the band

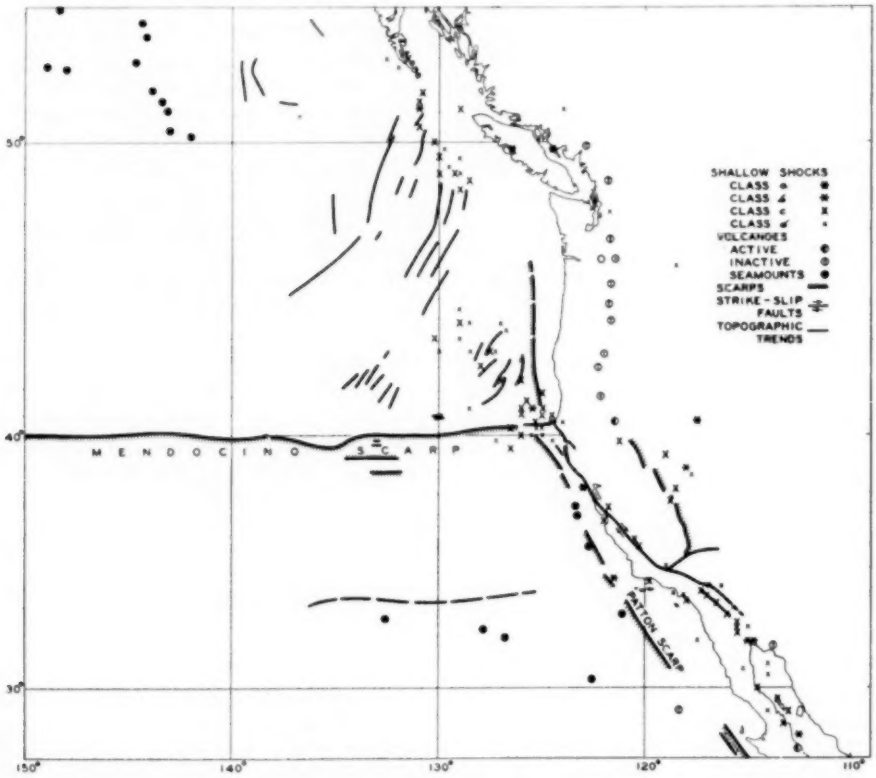


FIG. 4.—Tectonic pattern of the area around the Mendocino Scarp. Data on location and magnitude of earthquake epicenters from Gutenberg and Richter (1949).

of epicenters. Such depressions are commonly associated with the San Andreas fault on land.

ORIGIN OF THE MENDOCINO SCARP

No theory of the origin of the whole Pacific Basin gives a clue to the origin of the Mendocino Scarp, because none provides for the existence of a long scarp with a westerly trend in the northeastern Pacific area. Any speculation regarding the origin must draw on geophysical observations in the area, on regional tectonics extrapolated from shore, and on interpretation of imperfectly known topography; consequently, the most definite conclusions possible are nothing more than working hypotheses. A few hypotheses will be outlined and tested, but the testing will be brief, because few facts are available for the purpose. It might be taken for a fact, for example, that the Mendocino Scarp is very simple and straight; and conclusions as to origin might be based on that "fact." All that is known about the topography in this respect is that the scarp appears to be straight between widely spaced sounding lines. A similar spacing of sounding lines across the west face of the Wasatch Mountains would also show a long, straight, simple scarp instead of the complexly branching group of faults and scarps which has been found by more detailed mapping.

A few very large-scale features of the topography are firmly established by the soundings. An adequate hypothesis of the origin of the scarp should also explain these related features:

1. The sea floor for hundreds of miles to the south of the scarp is much deeper than for hundreds of miles to the north.

2. The scarp is the southern slope of a long asymmetrical ridge, and other asymmetrical ridges are parallel to the scarp on the north and south.

Among the many possible origins of the Mendocino Scarp and its associated topography, three seem worthy of consideration as working hypotheses:

1. The scarp marks the transition between "continental" rocks on the north and much more basic rocks on the south and is analogous to a continental slope.

2. The scarp marks a reverse fault produced by a north-south compression.

3. The scarp marks a strike-slip (transcurrent) fault.

"*Continental slope.*"—The deep portion of the sea floor south of the scarp has an area of roughly 350,000 square miles. The uniformly shallower sea floor to the north has an area of more than 1,000,000 square miles, or about one-third the size of the United States. Such large areas probably are in isostatic equilibrium, and the difference in depth on the two sides of the scarp probably reflects a difference in density of the underlying rocks. Evidence from other sources supports this conclusion. Gutenberg and Richter (1935) state that the propagation of seismic waves in the Pacific area between northern California and Alaska indicates that the area is "continental" in nature and seismically is not a part of the Pacific Basin. The deeper area off central California appears to be a normal part of the basin.

Recent geophysical investigations (Raitt, 1949, and oral communications) show that the Mohorovicic discontinuity is uniformly about 5 km. below the sea floor of the northeastern Pacific between San Diego and Hawaii and that from 10 meters to a possible maximum of 700 meters of "sediment" lie above the simatic[2] layer (velocity 6.7 km/sec).

[2] The term "sima" is used in the sense in which Gutenberg (1951) has recently defined it. It applies to crustal rocks which have a seismic velocity of between 6¼ and 8 km/sec and a density of about 3.0

The large area that Raitt studied off Baja California is, on the average, about 200–300 fathoms shallower than the deep sea floor off central California. Assuming isostatic equilibrium, a sima density of 3.0 gm/cc, an ultra-sima density of 3.3 gm/cc, and a negligible thickness of sediment, the difference in depth between the sea floor off central California and that off Baja California would be about 250 fathoms if the former region were devoid of sima. This agreement with the observed difference in depth suggests that off central California the sima is at most very thin. The relatively shoal depth of the sea floor north of the Mendocino Scarp, in turn, suggests that the sima is about twice as thick (10 km.) as it is off Baja California if the structure in the two areas is otherwise similar.

The writers do not intend to imply in the foregoing paragraphs that a portion of North America has subsided off Oregon and Washington. The depth of roughly 2,000 fathoms does not indicate that there is a sialic layer comparable to the layer under the continents; nor does the seismic evidence indicate such a layer (Gutenberg, oral communication). Moreover, no truncated seamounts (guyots) have been found off Oregon or Washington, nor has any other direct evidence of relative subsidence.

Granting rocks of different density to north and south, the Mendocino Scarp corresponds to a continental slope in position and relief, although not in depth below sea-level. A large submarine scarp recently reported by Tolstoy (1951) separates the terraced zone of the Mid-Atlantic Ridge from the deeper foothills and the "2,850-fathom plain" of the North American Basin. This scarp is as much as 8,100 feet high, and it lies on one side of a long, somewhat asymmetrical ridge. It resembles the Mendocino Scarp, and it may be another deeply submerged "continental slope"—dividing the Mid-Atlantic Ridge from the deeper sea floor of the Atlantic Ocean.

The Mendocino Scarp probably was formed in the same way as a continental slope. However, the origin of continental slopes is controversial, perhaps because there are several different origins. An initial slope must exist at the boundary between a high continent and the low sea floor, but the present continental slopes may be due to faulting or folding or deposition of sediment along the initial slope. The elongate, asymmetrical ridges in the vicinity of the Mendocino Scarp suggest that faulting of some sort has produced the present topography. The possible nature of the faulting is discussed below.

Reverse Faulting.—The general tectonic pattern of California may extend to the neighboring sea floor and thus provide a clue to the origin of the Mendocino Scarp. Faulting in southern California can be described in terms of a north-south compression (Gutenberg and Richter, 1949) which has produced many oblique, strike-slip shears, notably the San Andreas fault, and east-west reverse and thrust faults in the Transverse Ranges. Figure 5 shows a diagram of the forces acting in the vicinity of Cape Mendocino, assuming a dominant north-south compression. Whether these forces also act on the deep sea floor is uncertain, and it may be unreasonable

gm/cc. Petrologically, these are basalts and gabbros. Less basic rocks are called "sialic rocks" (density about 2.7 gm/cc and seismic velocity less than 6¼ km/sec), and more basic rocks are called "ultrasimatic" (density about 3.3 gm/cc and seismic velocity 8–8¼ km/sec).

to extrapolate them 1,200 miles to the outermost known portion of the Mendocino Scarp. However, Byerly (1940) believes that the San Andreas fault trend extends onto the deep sea floor, and Shepard and Emery (1941) have related the orientation of Davidson and San Juan seamounts off California to the tectonic pattern on the continent. Far beyond the known end of the Mendocino Scarp, the movement on the major faults on the western side of the Pacific is such that the oceanic area appears to be moving north relative to the continent (Gutenberg and Richter, 1949), suggesting that the same north-south compression is acting on both sides of the ocean.

If the Mendocino Scarp is undergoing a north-south compression, the scarp may be the trace of a reverse or thrust fault. Compressional faults on land typically have very irregular traces, unlike the Mendocino Scarp; but much of this irregularity results from prefaulting relief or postfaulting erosion. Granting an initially gently sloping, smooth sea floor and little erosion, the trace of a reverse or thrust fault might appear straight if surveyed on only a few widely spaced lines. The asymmetrical ridges could be formed directly as a result of reverse faulting. However, the present slope of the Mendocino Scarp is toward the south, and a reverse fault would dip toward the north. Consequently, sliding and slumping would be required to produce the present scarp. The debris should form an alluvial apron at the base of the slope, but none was observed on any of the "Horizon" crossings.

Any evidence which suggests that a north-south compression is acting in the northeastern Pacific area as well as in California increases the possibility that the Mendocino Scarp has been produced by reverse faulting. The northeast-trending ridges can be interpreted as giving such evidence. Figure 5 shows that the acute angle between the ridges and the general trend of the San Andreas fault is approximately bisected by the presumed north-south compressional forces. The geometry suggests that the ridges mark a set of shear faults which are complementary to the San Andreas fault.

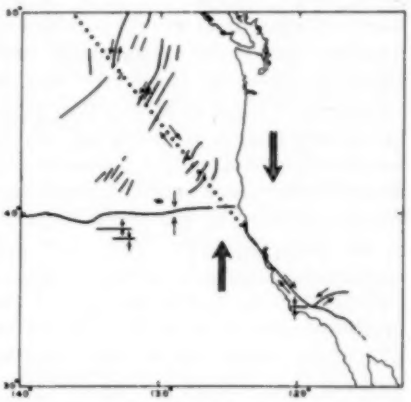


FIG. 5.—Mechanical interpretation of faulting and topography in the vicinity of the Mendocino Scarp. A north-south compression is assumed.

E. M. Anderson (discussion following Kennedy, 1946) states that, according to dynamical theory, strike-slip shear faults normally should occur in complementary classes symmetrically disposed at angles of about 25° on each side of the compression which produces the shears. He notes that good examples of this relation are found in the Santis Mountains and that a few strike-slip faults complementary to the Great Glen fault have been found in Scotland. The approximate angle between the ridges and the San Andreas fault (extended) ranges between 50° and 85° and averages about 65°. These angles are somewhat

larger than the values observed by Anderson, but any angle less than 90° is mechanically possible. The hypothesis of complementary shears appears to explain the otherwise anomalous trend of the ridges. The shoal depths of individual mountains rising from these ridges and the general trend and location of the mountains suggest that they were produced by the west-coast Pliocene-Pleistocene orogeny (Menard and Dietz, 1951). However, these ridges trend northeast, and the dominant trend of ranges and major faults produced by the same orogeny on land is northwest. It is not clear why the northeast shears should be prominent on the sea floor and not on the continent. In Scotland the development of northeast shears is favored by the general "grain" of the rocks (Kennedy, 1946), and few northwest shears are formed. Perhaps the "grain" in California favors the northwest shears, and the "grain" in the ocean basin favors the complementary ones. Figure 4 shows the more prominent northeast-trending ridges, and none are located west of about longitude 137° W., but low ridges with similar trends can be found on unpublished U.S. Coast and Geodetic Survey sounding lines as far west as longitude 155° W. A north-south compression appears to have acted across the full length of the Mendocino Scarp, if these ridges are along shears produced by such a compression.

Strike-slip faulting.—In a general way the scarp is very long and straight and has the appearance of a great strike-slip fault trace. However, many types of faulting produce traces which are straight in a general way. Strike-slip movement becomes probable if the fault is mapped in detail for long distances and is found to have no small sharp bends. The soundings in the vicinity of the Mendocino Scarp are spaced too widely to justify any conclusions regarding details of the trend of the scarp; therefore, the generally straight trace is by no means positive evidence of strike-slip movement.

Considered by itself, strike-slip movement could not produce a scarp about 1 mile high and 1,000 miles long, but appreciable vertical movement has occurred on both the San Andreas fault (Wallace, 1949) and the Great Glen fault (Kennedy, 1946), although the dominant movement on each is strike-slip. Neither of these great faults lies along an asymmetrical ridge, but elevations and depressions are rapidly leveled out by erosion and deposition on land, whereas they appear to be preserved in the deep sea for much longer periods.

The close juxtaposition of the very long, straight, strike-slip San Andreas fault and the very long, apparently straight Mendocino Scarp is suggestive of similar origin. Although the seismic evidence indicates that the San Andreas fault at present continues to the northwest from Cape Mendocino, it is possible that in the past the fault bent to the west and formed the Gorda and Mendocino scarps. Figure 5 shows that this possibility is remote because the very forces which produce a strike-slip shear in the direction of the San Andreas fault also produce a compression with no strike-slip component along the Mendocino Scarp.

CONCLUSIONS

The surveys by the Scripps Institution of Oceanography research vessel "Horizon" have served to tie together earlier spot soundings and to prove that a scarp extends west for more than 1,200

miles from Cape Mendocino, California. The scarp varies in height and is about 10,500 feet high at 70 miles offshore, and about 8,400 feet high at 1,000 miles offshore. The average maximum slope from top to bottom of the scarp ranges between 7° and 10°; but portions of the scarp 1,000 feet high have slopes as great as 18°–24°. The scarp lies on the south side of an elongate ridge which has a gentle slope to the north in most places. Other elongate sloping ridges with a scarp on one side lie parallel to the Mendocino Scarp both to the north and to the south.

The San Andreas fault appears to trend to the northwest from Cape Mendocino instead of bending to the west to follow the Gorda and Mendocino scarps. The scarp probably has formed along the contact between less dense rocks on the north and denser rocks on the south; it appears to be analogous in position and relief to the continental slope. The present topography of the scarp and of the associated long asymmetrical ridges may be due to reverse or strike-slip faulting along the initial "continental slope."

The outlines of the topography in the vicinity of the Mendocino Scarp are known only from the most generalized reconnaissance. Future surveys may find the details of the scarp to be far more complex than they appear at present. More parallel tilted blocks may be found, particularly to the south. If the foregoing discussion serves to focus interest on the northeastern Pacific Ocean as an inviting area for future geophysical and geological exploration, the writers will have realized much of their purpose in presenting this report.

ACKNOWLEDGMENTS.—The U.S. Navy Hydrographic Office and the U.S. Coast and Geodetic Survey furnished information on unpublished soundings which made it possible to prepare a bathymetric chart of the Mendocino Scarp. Moreover, the "Horizon" would not have surveyed in the area if reconnaissance soundings by ships of these two organizations had not given some indication that a scarp existed. The writers are informed by H. H. Hess that the U.S. Coast and Geodetic Survey soundings in this area were compiled by the late H. W. Murray and that he had in mind a new paper on the Mendocino Scarp at the time of his death. J. F. Frautschy and L. L. Garrison, on the first survey by the "Horizon," and J. D. Isaacs, W. S. Wooster, J. Barandiaran, C. V. Simmons, A. C. Smith, and H. B. Stewart, on the second survey, all co-operated in monitoring the fathometer. Captain J. L. Faughn, of the "Horizon," did the detailed navigation with Loran and star fixes which gave the surveys meaning. Roger Revelle, who led the expedition to the mid-Pacific, encouraged and helped to organize the first survey.

M. P. Billings, J. P. Buwalda, H. H. Hess, F. B. Phleger, and F. P. Shepard have been kind enough to read a preliminary draft of the manuscript—based on the first survey alone—and to make suggestions for its improvement.[3]

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[3] Eight months after the first survey and 2 days after the preliminary (then presumed final) draft had been forwarded to the editor, Mr. Warren Wooster informed the writers that the Scripps Institution of Oceanography was organizing an expedition to northeastern Pacific waters which would

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have time for a resurvey of the Mendocino Scarp. Lest this sort of thing should continue year after year, the present draft of the manuscript is being written at sea only a few days after completion of the second survey.

GEOLOGICAL NOTES

A SOLUTION CAVE IN GYPSUM[1]

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University of Chicago

The main chamber of Alabaster Caverns, Woodward County, Oklahoma, has a capacious, nearly horizontal passageway about ½ mile long, wholly in massive, coarsely crystalline gypsum. The cave possesses at least four features of phreatic origin, on which are superposed five other features of vadose origin. The similarity to such in limestone and dolomite caves is very close and indicates that any soluble rock of sufficient strength now above the water table may possess solution cavities recording the two unlike experiences with ground water.

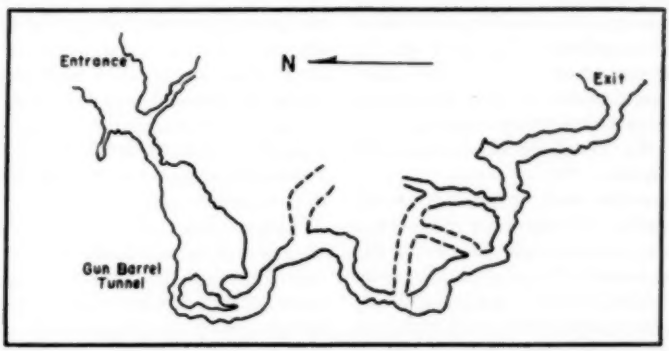

FIG. 1.—Ground plan of main chamber of Alabaster Caverns

Alabaster Caverns lie under parts of Sections 28 and 33, T. 26 N., R. 18 W., 5 miles south of the town of Freedom, Woods County, Oklahoma, and about 50 feet below the upland margining the Cimarron River Valley. The main chamber is wholly in the Medicine Lodge gypsum member of the Blaine formation of Permian age. The entrance and exit openings, about ¼ mile apart in a straight line, are in collapse sinkholes (ponors) that penetrate through the overlying Shimer gypsum member of the Blaine formation and the unnamed shaly member which separates the two gypsums. A smaller and horizontally less extensive chamber lies in the Shimer above the shale. The main chamber's perennial stream descends to a still lower horizontal passage close to the top of the underlying Flowerpot shale. All the vertical connections between the three stories appear to be of collapse origin.

The surveyed ground plan of the main chamber (fig. 1) shows angularly curvilinear passages, suggesting joint control, although joint cracks in the ceilings are not prominent. The survey covers but little of the cave's network pattern. Most lateral openings off the visitor's route are only crawlways. Many of these end in detrital

[1] Manuscript received September 21, 1951.

blockades, where continuation of the solutional openings is obvious but untraversable. The cave stream's fairly recent removal of detritus along the mapped passages has provided the only practicable route for human traverse. Not far back in its history, Alabaster was filled to all ceilings with debris.

Extensive failure of wall and ceiling rock has modified most original outlines, and the detrital deposits have added to the difficulty of mentally reconstructing the solutional form of the chamber's cross section. Solutional attack on ceilings to make the domelike concavities, one of the cave's phreatic features, has in several places penetrated to the base of the shaly member. Consequent on this has been local failure of the shale to make much higher domed-ceiling cavities, wholly of collapse origin. Most of these have migrated up to the base of the Shimer gypsum, and some can be climbed through to reach the upper chamber. They are broadest in their uppermost portions, some being nearly twice as wide there as in the top of the Medicine Lodge gypsum member.

Water for the cave stream enters the mapped portion of the cave at several places. Some of these are laterals of the network, and one of the superposed vadose features of Alabaster is a very steep, very narrow gully cut down across wall rock from the hanging mouth of a phreatic lateral. The stream itself takes origin somewhere under the upland south of the visitors' exit opening and enters the main chamber through a mass of collapse blocks at the bottom of the ponor there. No opening for human passage has been found among these blocks, but excavation very probably would allow one to pass the blockade and enter a further extension of the main chamber in that direction. Because both the entrance and the exit ponors clearly are failures of roof rock over an already capacious cave, the present termini of the main chamber surely are not original termini. There is more to Alabaster south of the exit opening, and there originally was more at the north end, where the cave is transected by Cedar Canyon.

There are numerous sinks in the coarsely crystalline Shimer gypsum near the southern end of the mapped cave. They appear to be compound forms: earlier broad, shallow, wholly solutional cavities (dolines), in the bottoms of each of which may be several small ponors. Explorers have descended some of these to enter the upper cave chamber and thence, by making horizontal traverses, to reach the main cave through a ceiling collapse dome. At least one of these smaller openings is literally a swallow hole, wholly solutional and showing no collapse.

Although caves in gypsum are rare, several are reported from this vicinity in one or the other of the two gypsum members. Among them, Alabaster certainly antedates the development of the surface sinks. This assertion is based largely on the evidence for phreatic origin of the main chamber, an origin antedating the present stream-carved topography which has been responsible for lowering the water table, for initiation of the cave's vadose history, and for making the sinkhole topography.

Judged from the writer's experience, spongework in cave walls is a common feature of caves in dolomite but is rare in limestone caves.[2] Spongework in Alabaster is rather poorly developed and consists of fairly equidimensional concavities which rarely overlap and nowhere unite with one another back in the wall rock. Perhaps these solution pits of Alabaster should have a different name. That they are older than the work of the free-surface stream now using the cave is obvious from their modification by current flutes and their near-destruction by meander niches, both of which vadose features are repeatedly shown on unfailed wall rock.

The wholly solutional ceiling cavities previously mentioned as of phreatic origin

[2] Clyde Malott, author of the invasion theory of cavern development (1938) and authority on limestone caves in Indiana and Kentucky, told the writer that he had never seen spongework.

are matched by wall cavities dissolved back along minor and otherwise unopened joints. The vadose current flutes on wall rock are even more definitely affected in distribution and degree of development by wall cavities than by the smaller spongework cavities. In both cases there were cavities in the wall before the stream flutes were made.

Only one showing of bedding-plane anastomosis was found. It is near that detail of the network pattern called the Gunbarrel Tunnel. A large fallen ceiling block has split off along the plane affected by the anastomosis and reveals an intricate plexus of minor water routes, once functioning along this leaky plane. Upward solution into the overlying stratum is almost as well shown here as in the Ste. Genevieve limestone of Mammoth and other Kentucky caves (Bretz, 1942, pp. 706–708).

Current flutes are common where original cave walls converged downward and afforded a rock bottom for the vadose stream. In form they duplicate current ripples in sand of a stream bed, being steeper on the downstream side. Although solutional forms, they should be considered as equilibrium profiles made under turbulent flow, identical with those being made today by vadose streams in many limestone and dolomite caves.

Pendants of native rock exist in a few places. Like those in caves in calcareous rock, they are taken to be a consequence of vadose water brought up against a ceiling by aggradation of the floor, the flowing water etching out a pattern of anastomosing small, irregular passages instead of becoming confined to one channel, as in the wall and ceiling channels described in the next two paragraphs.

Alabaster possesses many meander wall niches, some undergoing development today and many abandoned high and dry on the phreatic walls. The outstanding example is partially obscured by a remnant of the cave's detrital fill. It is unique in the writer's experience, in that the grade of the vadose stream was being *raised* by aggradation of the cave floor at the time the niche was made. The meander, caught in its curvilinear niche in the cave wall, was forced to dissolve upward into the wall rock. Thus the slip-off slope inside the meander but outside the phreatic chamber hangs *upside down*. The nearest comparison in form which the writer knows of is the group of upside-down meanders in the ceiling of Endless Caverns, Virginia (Bretz, 1942, pp. 740–741). Alabaster's feature, however, is in the wall. Its stream escaped the trap after some 4 feet of upward erosion had occurred along the meander.

A much more conspicuous channeling by the vadose stream is displayed in the ceiling in the same part of the cave. Deposition of clay, silt, sand, and gravel here finally raised the stream bed all the way up to the earlier solutional ceiling. Confined between a bed of insoluble debris and a ceiling of soluble rock, it had no option but to dissolve a passageway up into that ceiling. Few caves show so strikingly the *upward* channeling which must ensue in a filled cave that still is the logical route for a vadose stream.

The detrital fill still remaining in Alabaster is entirely a vadose stream product, made since the water table dropped below the phreatic cave level. No trace was seen of a phreatic clay fill deposited when reduction of relief in the overlying topography so reduced the hydrostatic head in the saturated rock that the slow phreatic circulation came essentially to an end. The gypsum, shale, and sandstone of the region appear not to have yielded a clay of almost colloidal character to be deposited in the nearly motionless water still filling the cave.

Instead, this cave underwent an experience comparable to that of those Black Hills caves which the writer has studied. It became a great geode at a stage intermediate between its phreatic solution and its vadose experiences. Masses of clear selenite, up to 2 feet thick, were deposited in a mosaic of interlocked large crystals on walls and interstitially among great blocks of wall and ceiling rock which had already fallen. The largest individual crystal seen

was 24 inches long and 12 inches wide. Most of these masses have undergone subsequent solutional smoothing and cupping, but a few possess surviving outlines of original crystals projecting into the cave.

An enameling of wall rock with a thinner deposit of smaller and cloudy interlocked crystals is prevalent throughout most of the cave. This selenitic plating on Alabaster's surviving phreatic surfaces is taken to record that episode of almost static phreatic water which the writer has argued from the red-clay filling of limestone and dolomite caves, an episode brought about by an old-age reduction of relief in the overlying topography.

One of the most common features of vadose alteration of calcareous caves is dripstone, flowstone, rimstone, and other secondary lime deposits. None of these forms was seen in this calcium sulfate cave, not even gypsum flowers. The management of Alabaster assured the writer, however, that rimstone exists in remote and difficultly accessible parts of the cavern system and that stalactites, 3 feet long and "as thick as a man's arm," are known in one of the neighboring caves. The commonly asserted idea that dripstone and related forms are deposited because of loss of CO_2 can never be applied to air-deposited secondary cave gypsum.

Steeply inclined partings in the wall rock, rudely parallel to wall faces and in some cases constituting separated slices still standing, may be ascribed to expansion from hydration of an anhydrite fraction still in the gypsum rock. Apparently due to the same cause are the "geyser domes" on bare, essentially horizontal bedrock surfaces on the floors of dolines and on benches along Cedar Canyon. These are low, hollow domes a few feet across and a foot or so high, the surface rock having been buckled up at the intersection of two joints.

Alabaster Caverns' phreatic history should date back to a time when the lowland of this region lay at least as high as the summits of the scattered buttes of Dog Creek shale, with their capping of Whitehorse sandstone. The Blaine formation was then entirely in the saturated zone, and the only movement was a slow hydraulic circulation from beneath the uplands toward the Cimarron Valley of that time, perhaps an artesian circulation because of the shale units in the stratigraphy. Most of the void space of Alabaster is believed to have been made under such conditions.

The three stories of the cave are not to be interpreted as sequential in origin, consequent on the lowering of the water table. The upper story has a shaly member as a floor, as befits such an interpretation, but the main chamber level is well up toward the top of its gypsum member instead of occurring at the base in contact with the underlying Flower-pot shale. All three levels are held to have been developed at the same time under completely saturated conditions.

Erosional lowering of the earlier uplands and intake areas eventually brought that deep circulation so nearly to a standstill that water in the passages became saturated and deposited the crystalline overlay, which still remains on phreatic solution surfaces.

With initiation of the present cycle of erosion, the Cimarron River started deepening its valley toward the lowered base level. Concomitantly, the water table was lowered, and Alabaster came to have air in it for the first time, its water now moving as a free-surface, gravity-directed stream on the cave floor.

The episode or episodes of sand and gravel filling seem to require an aggradation in Cimarron Valley as the cause. Vadose history underground should tie in with physiographic history above ground. This is an interesting relationship to consider when Cimarron Valley's physiographic record is studied.

A more detailed study of Alabaster may show that its main chamber has had two experiences with phreatic conditions, alternating with two vadose experiences. It would seem probable that, when the detrital

fill was mounting to the level of the upside-down ceiling channel, the water table in the enclosing rock was correspondingly rising. Interstitial selenite in this stream-deposited fill may record such a condition, a second phreatic episode dating from the hypothetical aggradation in Cimarron Valley. But the only phreatic solution that could occur during this second subwater-table experience would be limited to cavern laterals not entered by the sink-contributed stream debris. Although superposition of vadose solutional features on those of phreatic origin is fairly common, the writer has never found the sequence reversed.

Had the writer been uninformed and were the expansion from hydration lacking and the crystalline gypsum sufficiently fine-textured to have escaped notice, he probably would have left Alabaster Caverns without suspecting that it was not a limestone or dolomite cave. Given a horizontal stratiform structure, it appears that cave forms and their associations and sequences are determined by the behavior of ground water in soluble rock. Certainly this cave in gypsum carries a good record of the two epochs originally proposed by W. M. Davis (1930): an early phreatic development and a later vadose modification. The secondary crystalline gypsum should correspond with the intermediate epoch described elsewhere (Bretz, 1942, pp. 773-777) as the epoch of clay filling.

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AGE OF SUBSURFACE "TAMIAMI" FORMATION NEAR MIAMI, FLORIDA[1]

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On the basis of data obtained during an investigation of the geology and water resources of southeastern Florida, Garald G. Parker and C. Wythe Cooke, of the United States Geological Survey, made in 1944 a correlation of the shallow subsurface materials in southeastern Florida. They (1944, p. 64) traced surficial outcrops of the Tamiami formation from W. C. Mansfield's (1939, p. 8) typical localities in Collier and Monroe counties, eastward in the banks of the borrow ditch of the Tamiami Trail (U.S. Highway 41) into western Dade County, where the formation dips gently beneath younger materials. From this area, near the Everglades–Big Cypress Swamp border, the Tamiami was correlated, by subsurface data obtained from test wells drilled by cable-tool rigs, with the highly permeable rocks that unconformably underlie the Miami oölite of Pleistocene age in the Miami area. Mansfield considered the Tamiami to be of basal Pliocene age and tentatively placed it below the Caloosahatchee marl—also of Pliocene age.

In southeastern Florida, gray freshwater limestones containing an abundance of shell molds were first noted in cores of these highly permeable rocks from wells southwest of Miami, drilled in 1947. Subsequently, core borings from test wells west

[1] Published by permission of the Director, United States Geological Survey. Manuscript received July 19, 1951.

of Miami also showed fresh-water limestone intercalated with the marine limestone. Data concerning the occurrence of these fresh-water limestone beds in the Miami area are still skimpy but strongly suggest a Pleistocene age for these deposits. Therefore, a tentative change in correlation is here presented.

Dense fresh-water limestone, gray in color, was observed in the cores of well G 551 between 37 and 38 feet below mean sea-level, where it was attributed to cavity-filling, and as a bed 0.2 foot thick at 50 feet below mean sea-level. Fresh-water limestone, 0.5–1.2 feet thick, was penetrated in four core borings in Miami's southwest well field (see fig. 1) at depths of between 39 and 41 feet below mean sea-level. The base of the highly permeable aquifer in these five wells is about 90 feet below mean sea-level.

Cores from well G 607 adjacent to well G 608, west of Miami, contained five beds of tan-colored, very hard limestone, ranging from 0.5 to 3 feet in thickness. The three uppermost beds contain an abundance of molds of fresh-water gastropods; the lower two beds contain no identifiable

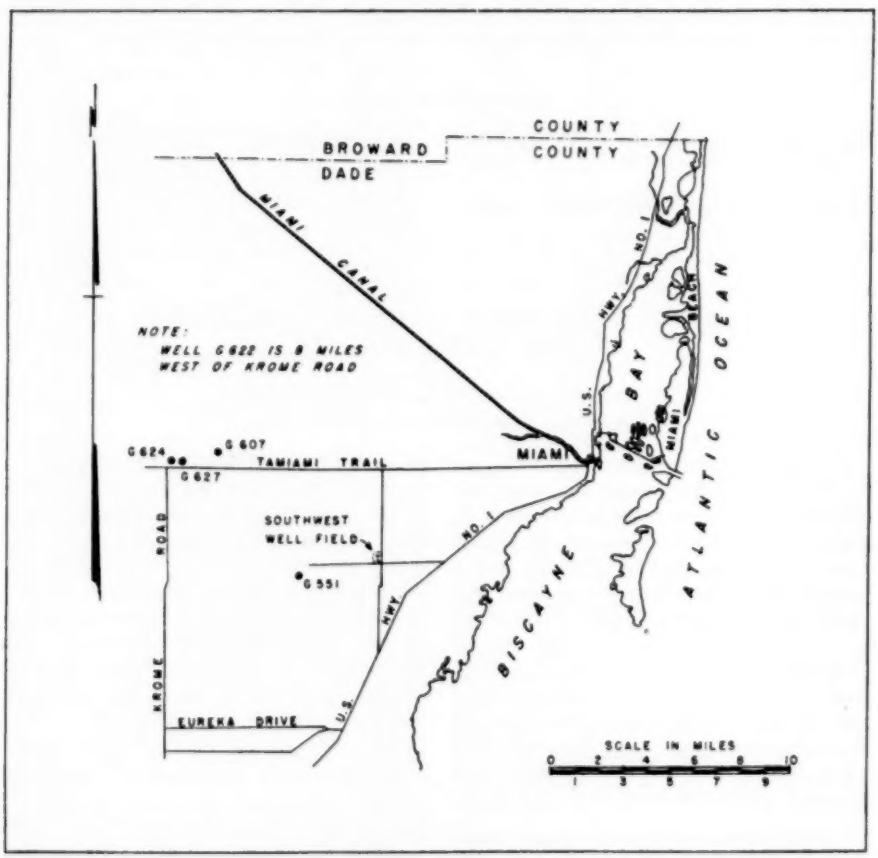

FIG. 1.—Miami, Florida, and vicinity

fossils. However, 2 miles to the west, near Krome Avenue and the Tamiami Trail, all five beds contain an abundance of fresh-water gastropods (see fig. 2). The highly permeable aquifer in this area is encountered at a depth of about 3 feet below mean sea-level, and the lowest fresh-water limestone is from 1 to 4 feet above the base of the aquifer. Cores from well G 622, 8 miles west of Krome Avenue, contained three beds of fresh-water limestone, one being separated by an unconformity.

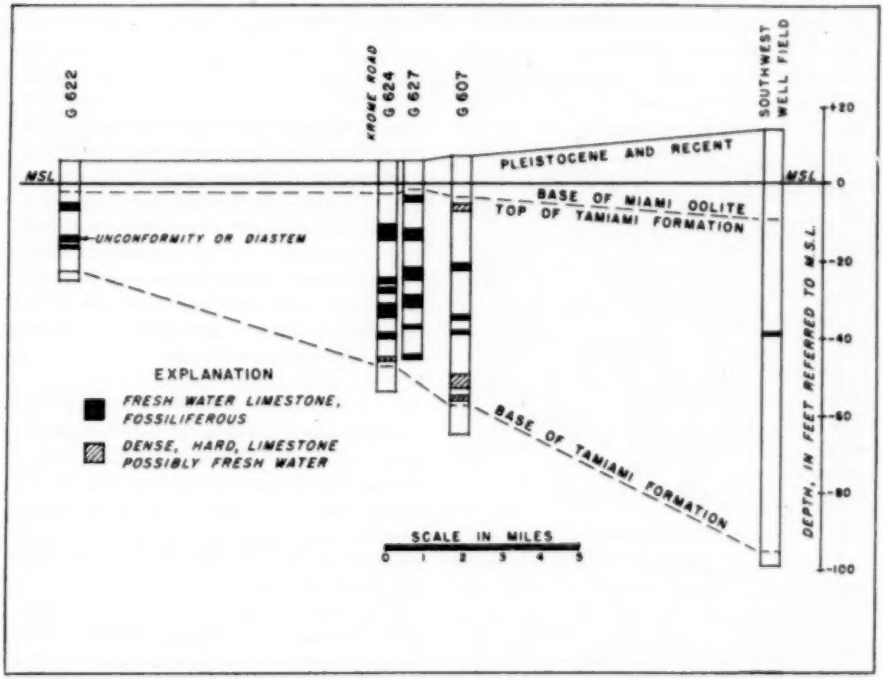

FIG. 2.—Geologic cross section in the vicinity of the Tamiami Trail, Dade County, Florida

Fresh-water beds have not been reported in the Pliocene of the Atlantic Coastal Plain, and they do not occur in the Caloosahatchee marl in the outcrop area, although fresh-water shells are found, in places, mixed with marine forms. However, alternating marine beds and fresh-water marl of the Fort Thompson formation, which overlies the Caloosahatchee marl unconformably, have been tentatively correlated by Parker and Cooke (1944, p. 89) with the interglacial and glacial stages, respectively, of the Pleistocene. Fresh-water limestones are found at depth in the highly permeable aquifer of the Miami area and to the west in the Everglades. Their presence certainly suggests, although it does not prove, that a major part of the rocks heretofore assigned to the Tamiami formation as used by Parker and Cooke is not of Pliocene age but is Pleistocene—equivalent in part, at least, to the Fort Thompson formation. It also suggests that the Tamiami formation of Parker and Cooke should thus be restricted only to the basal portion of the highly permeable aquifer below the lowest fresh-water bed and that the major part of the aquifer is a highly permeable and greatly thickened southward extension of the Fort Thompson formation.

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VERTEBRATES FROM THE SAN ANGELO FORMATION EARLY PERMIAN OF TEXAS[1]

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INTRODUCTION

Field work during 1950 and 1951 disclosed identifiable remains of fresh-water and terrestrial vertebrates in the San Angelo formation in Knox and Hardeman counties of Texas. Fossiliferous beds are exposed along Little Croton Creek, on the MacFayden ranch southwest of Benjamin, in Knox County, and on the north bank of the Pease River, east and west of the Crowell highway, 10 miles north of Crowell, in Hardeman County. Both localities were pointed out to the writer as promising for vertebrates by Dr. Robert Roth, of the Humble Oil and Refining Company.

STRATIGRAPHY

Roth (1945) published a section, including the San Angelo formation, measured along Little Croton Creek. The details of this section can be generalized for our purposes to include a lower part of the formation, consisting largely of green and gray sandstone about 60–70 feet in thickness; a middle part, consisting of about 20 feet of red shale with some interbedded grits; and an upper part, 40–50 feet thick, of green sandstone, coarse brown grits, and clay-ball conglomerates. The section at the Pease River locality is similar, but the red-shale portion is thinner. In both localities rapid lateral variation of beds is characteristic.

The San Angelo, in the areas studied, overlies the Choza formation of the Clear Fork group disconformably. In places the formational boundary may be readily discerned (see, e.g., Roth, 1945, figs. 1, 2), but at others, particularly at the Little Croton Creek locality, the precise position of the contact is obscure. Overlying the San Angelo formation, with a somewhat transitional boundary, is the Flower-pot shale. Its basal part is composed of anhydrite-rich red shale. A cursory examination failed to reveal any organic remains.

VERTEBRATES

Fragmentary remains of vertebrates are widely scattered through the upper part of the San Angelo and are present, but rare, in the red shale. The lowest part appears to be virtually unfossiliferous. Identifiable specimens are uncommon and, as a rule, broken and disarticulated.

With the exception of the fresh-water shark *Xenacanthus*, represented by a few teeth, all genera now known from the San Angelo are new to the Texas area. The genera and species will be described and figured in a subsequent paper. The following discussion is confined to general comments on the fauna.

No vertebrates definitely identifiable as amphibians have as yet been found. All reptiles in the collections are referable to the subclass Eureptilia and distributed between the infra-classes Captorhina and Synapsida. There are two genera of Captorhina, both of which may be referred to the large family Captorhinidae. One is known from a skull that measures about

[1] Manuscript received October 9, 1951.

240 mm. in length. It is characterized by maxillary and dentary tooth plates composed of irregular rows of sharp, conical teeth. Two vertebrae, found at a different site from the skull, may also pertain to the genus. The closest affinities of this genus appear to be with *Labidosaurikos* Stovall, which is known from the Hennessey shale of Oklahoma and the Vale and Choza formations of Texas. The resemblances appear to be somewhat superficial, however, and may be due in large part to adaptive similarities. The second genus is known from two specimens. One consists of a partial skull and lower jaw, anterior vertebrae, and a partial shoulder girdle; the other includes six presacral vertebrae and unidentified fragments. This genus has no close affinities with any other known genus of the family Captorhinidae.

The synapsids include two types of edaphosaurian pelycosaurs, referable to the family Caseidae, and a carnivore of less certain ordinal and familial position. One of the caseids is known only from a single humerus. This bone closely resembles the humerus of *Cotylorhynchus* from the Hennessey shale of Oklahoma. Although *C. romeri* from the Hennessey has been the largest known pelycosaur to date, the San Angelo humerus is one-fourth to one-third larger, based on length and width dimensions, than the largest known Hennessey specimen. It probably belongs to a different species. The other caseid is known from a partial skeleton discovered in the red shale. It was a large, heavy, short-legged animal that bears no close resemblance to any other known genus of caseid.

Three specimens of a moderately large carnivore, with a skull perhaps 200 mm. in length, have been found in the sandstones of the upper part of the formation. All are fragmentary. The best consists of a pair of lower jaws with slender rami and a broad symphysial region. Dentition consists of a single large "canine" and a series of seven or eight ovoid cheek teeth. A number of features suggest therapsid affinities, especially the dentition, the nature of the symphysial region, and the extent of the dentary. Each of these characters may be interpreted as adaptive and could have been derived from some sphenacodont pelycosaur. Because, however, all depart from the sphenacodont level toward a therapsid condition, it appears that this genus might best be considered a therapsid. It is probable that it reached this level independently of the Old World therapsids.

In addition to the animals just considered, there are fragmentary remains of others, not yet sufficiently known to warrant discussion. None of these appears to belong to any of the well-known genera from the underlying Clear Fork formations.

One exceedingly puzzling specimen, which consists of a well-preserved vertebra, a partial humerus, frements of other vertebrae, ribs, and indeterminate fragments, has come from the very top of the section at the Little Croton Creek locality. At a distance of about 100 feet, in what appears to be essentially the same horizon, remains of Pleistocene mammals occur. Both are in the soil zone. The specimen is highly mineralized, resembling other San Angelo specimens in this respect, and is distinctly reptilian both in the vertebra, which is deeply amphicoelous, and in the humerus. Thus the evidence from associations and from morphology are in conflict. The animal was decidedly larger than any heretofore known from the North American Permian and approaches the largest dinocephalians and anomodonts in general proportions. It is unlike any other reptile with which comparisons have been made. If this reptile was of San Angelo age—and any other interpretation poses serious difficulties—it marks a striking departure from anything previously known in the early Permian. It is hoped that future field work will aid in the solution of this enigma.

EVOLUTIONARY AND STRATIGRAPHIC POSITION OF THE FAUNA

The San Angelo fauna is distinctly different from the fauna that persisted throughout much of Clear Fork time in Texas. In

the presence of the genus *Cotylorhynchus*, it shows continuity with the Hennessey shale of Oklahoma, but it is different in all other respects. The nature of the deposits suggests nondeltaic conditions of deposition, except possibly for the red-shale facies. This may in part account for the differences of the fauna from that known in the Clear Fork, which was predominantly deltaic. There can be no doubt, however, that the San Angelo fauna is well advanced in the evolutionary scale over the Clear Fork and Hennessey faunas, and it appears to include a number of adaptive counterparts of the middle Permian faunas of Russia and South Africa. These, almost certainly, were independently derived. The fact that such terrestrial types as *Dimetrodon*, common in the Clear Fork, have not been found suggests a real break with the underlying formations. The absence of such animals as *Lysorophus* and small captorhinomorphs suggests a marked difference from the Hennessey of Oklahoma. Evidence that there was a reasonably long interval of time between the deposition of the Choza and Hennessey formations and the San Angelo seems reasonably strong.

This evidence of a time break has bearing upon the stratigraphic relationships of the formation. Roth (1945) established the "Pease River group," with the San Angelo as the basal formation. He suggested, partly on physical and partly on biological evidence, that the Pease River group was post-Leonard in age. Earlier (Roth, 1942) he had placed the San Angelo in the Leonard formation, following more standard practice. The vertebrate evidence gathered to date strongly supports Roth's later position, that the San Angelo formation must be considered post-Leonard in age.

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DIFFUSION IN PLAGIOCLASE FELDSPARS[1]

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Zoned plagioclase crystals are relatively common in many types of igneous rocks, including granites. Their origin will not be discussed here; the view that these crystals grew in contact with a melt (i.e., from a magma) has met with but little serious opposition since it was first proposed by Vogt in 1903. Rather recently, however, the writer has occasionally run across the opinion that the persistence of zoned plagioclases is excellent evidence that solid diffusion cannot be a significant process in rock modification or formation. The presence of these inhomogeneous crystals (many with very sharp zonal contacts) in ancient rocks does, on first thought, make it appear that little or no reorganization could have taken place in these rocks; diffusion over a very small distance would eliminate the compositional differences expressed by the zoning. Consideration, however, of the changes that are necessary to bring about homogenization of plagioclases illustrates the difficulties involved in this process.

Any single plagioclase composition has, in addition to a specific Na:Ca ratio, a specific Al:Si ratio, the two ratios being interdependent. In the range from albite ($NaAlSi_3O_8$) to anorthite ($CaAl_2Si_2O_8$) the Al:Si ratio changes from 1:3 to 1:1. Thus, to homogenize a zoned plagioclase crystal

[1] Manuscript received January 3, 1952.

or, in the general case, to attain solid-state equilibria between any differing plagioclase compositions, not only must the Na^+ and Ca^{++} ions be rearranged, but at the same time Al and Si must be redistributed. In framework alumino-silicates, such as the feldspars, the tetrahedrally co-ordinated Al and Si atoms form Al-O and Si-O bonds that are the strongest bonds in the crystal. The Si-O bonds in particular are exceedingly tenacious; it is now well known that the SiO_4 tetrahedral unit, from which the structures of all silicates are built, persists even in silicate melts. To remove and migrate a silicon atom from its "imprisoning" four surrounding oxygen atoms by thermal energy alone is exceedingly difficult. To move it along with its co-ordinating oxygen atoms in a network silicate (at least in large enough quantities to produce an appreciable compositional change in the crystal) requires extensive reorganization of the structure. The *least* drastic of the structural changes of a type that requires reoganization of the tetrahedral units are certain of the reconstructive polymorphic transitions, and the sluggish nature of these transitions is well known. The process of Al-Si order-disorder in silicates is also a change that involves but little actual movement (although more than in the case of a simple reconstructive transformation), yet one that requires a large energy input to overcome the strong bonding forces involved. Many examples illustrating the tenacity of the tetrahedral framework bonds could be given.

The energy required to move the Na and Ca and therefore the Al and Si atoms to those positions necessary to attain homogeneity in even a small crystal is indeed large. Many tetrahedral bonds must be repeatedly broken, and migration over sizable distances (in terms of the unit cell) must take place. It is improbable that diffusion of this sort can take place within the crystal much below the melting range of the lowest-melting constituent (i.e., the most albitic portion) of the crystal. Dittler and Kohler (1925), in a study devoted chiefly to the alkali feldspars, examined a zoned plagioclase before and after heat treatment. The crystal was from a diorite-porphyry and had sharp zonal contacts; the total composition ranged between 20 and 70 per cent anorthite. Heating for 500 hours at 1,000° C. produced no visible change; the sharp contacts between zones remained sharp. The sample was then heated for 1,000 hours, again with no change. Although it is realized that in terms of geologic time a short heating period was involved, it should be noted that 1,000° C. is geologically a very high temperature, and this experiment well illustrates the problem. The fact that large, sharply zoned plagioclase crystals are found at all in rocks is a good measure of the extreme sluggishness of the Al-Si diffusion process. Many of these crystals must have been subjected to magmatic temperatures for long periods of time, as well as to a long, slow cooling; yet sharp borders commonly persist into the core of the crystal.

The large energy barrier that inhibits diffusion in the plagioclases is not present in the alkali feldspars. The feldspars $NaAlSi_3O_8$ and $KAlSi_3O_8$ have the same Al:Si ratio. The process of unmixing of alkali feldspar solid solutions or, conversely, the homogenization of exsolved or coexisting potash-rich and soda-rich feldspars involves only alkali diffusion. Only if the two feldspars are structurally similar, however, is homogenization accomplished with great ease. Laves (1951*a*) has pointed out this fact and has made use of it to produce microcline from a crystal of low albite by the process of alkali diffusion. Dittler and Kohler (1925) describe the relative ease with which even those perthites showing coarse separations could be homogenized. The moderate temperature required for homogenization of certain cryptoperthitic intergrowths (of the same structural type[2]) is also shown in the work of Spencer (1937); Bowen and Tuttle (1950) describe how readily remixing can take place at temperatures above the solvus in the system $NaAlSi_3O_8$-$KAlSi_3O_8$. An example of a difficult type to homogenize

[2] A paper on this subject by F. Laves is now in preparation.

would be an intergrowth of orthoclase and low albite; it is here assumed that the former for the most part is disordered with respect to Si-Al, the latter ordered. That these assumptions appear justified is discussed by Laves (1951*a*, *b*, *c*). The point to be made is that even this pair, difficult as it is to homogenize because of the structural reorganization involved, presents much less difficulty than do the plagioclases, in which appreciable movement of Si and Al must take place. It is perhaps also worth noting that the antiperthites (intergrowths of potash feldspar and plagioclase) would tend to retain their two-phase identity at anything but severely high temperatures, not only because of the inherent instability of a solid solution at lower temperatures but also because of the different Al:Si ratios in the two phases.

Chao and Taylor (1940), on the basis of X-ray evidence, were the first to indicate that intermediate plagioclases may consist of two interlaminated plagioclases, one albitic, the other anorthitic. In a recent paper, Cole, Sörum, and Taylor (1951) presented additional data, refining and strengthening this interpretation. Of the samples they investigated, one labradorite phenocryst from a lava flow proved to be a single phase; heating of an "inhomogeneous" labradorite (70 hours at 1,100° C.) removed all but a few of the most intense subsidiary X-ray reflections that are indicative of nonhomogeneity. If this phenomenon disclosed by the X-ray photographs is an "unmixing," it is significant that it never results in sizable separations of the two phases, as is so often the case with other solid solutions that unmix. The exceedingly fine lamellae are resolved only by X-rays, and the coexistence of two different plagioclase compositions as macroscopic or microscopic crystals under equilibrium conditions is unknown to the writer.[3] Plagioclase phenocrysts that differ in composition from the groundmass feldspar represent a nonequilibrium situation that is to be expected, particularly in the light of this discussion. There is also the related situation in which two plagioclases might exist out of equilibrium as a result of two generations of mineral development. If it is assumed, however, that intermediate plagioclases are unstable and tend to unmix to two plagioclases at low temperatures, it is unlikely that extensive physical separation of the two phases would take place, for the same reason that the reverse process—homogenization—is so difficult.

It is thus seen that atomic or ionic movement in dry plagioclases is very hard to bring about. Although in the alkali feldspars diffusion of the alkali cations is, by comparison, much easier, extensive reorganization of the Al and Si is quite difficult if no flux is present, and it is unrelated to the alkali movement. It is not intended in this presentation to imply that solid-state diffusion is a common rock-forming process; for, as an example, the production of a granite from a pre-existing rock in the general case would require a sizable change in the Si:Al ratio. It would thus appear that any extensive reorganization by diffusion in the dry state in a system composed principally of tectosilicates would be a process limited to rather high temperatures. The crystallographic difficulties involved in migrating Si and Al to the extent necessary for rock transformation would seem to be sufficient to nullify the arguments in favor of dry diffusion as a rock-forming process where a change in the Al:Si ratio is involved. It is perhaps illogical, however, to use the persistence of zoned plagioclases as negative evidence that diffusion is inoperative, as a considerable amount of cation diffusion might well take place before a plagioclase would be noticeably changed.

[3] The problem of the apparent stability of two plagioclases below certain temperatures and the conflicting evidence that two plagioclases are not found crystallized separately at low temperatures will not be discussed here but is at present undergoing laboratory investigation. This is tied in with the problem of the low-temperature hydrothermal breakdown of plagioclases.

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REVIEWS

Marine Geology. By PH. H. KUENEN. New York: John Wiley & Sons, Inc., 1950. Pp. x+568; figs. 246; pls. 2. $7.50.

Marine Geology fills a very timely need, as no comprehensive book on marine sedimentation and geology has appeared since *Recent Marine Sediments* was published in 1939. The book is particularly welcome because it also contains chapters on marine morphology and tectonics. It is replete with illustrations and contains abundant references to the literature. Special emphasis is placed on the Dutch East Indies, in which the author has had much experience, but adequate reference to other parts of the world is given as well. The book is divided into eight chapters: "Physical Oceanography" (89 pp.); "Morphology and Geology of the Ocean Basins" (85 pp.); "The Indonesian Deep-Sea Depression" (35 pp.); "Sources and Transportation of Marine Sediment" (92 pp.); "Environments of Marine Sedimentation" (112 pp.); "Coral Reefs" (66 pp.); "Submarine Valleys and Marine Volcanism" (52 pp.); and "Eustatic Changes of Sea Level" (13 pp.).

The development of subject matter is stimulating. The author attempts to give plausible explanations for the phenomena described. Obviously, in a subject in such an early stage of development as marine geology, definite answers cannot yet be given to many questions. Students with experience different from Kuenen's may not agree with some of his hypotheses, but they cannot read the book without profit to themselves.

PARKER D. TRASK

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A Laboratory Manual for Geology; Part I: *Physical Geology*. By KIRTLEY F. MATHER, CHALMER J. ROY, and LINCOLN R. THIESMEYER. New York: Appleton-Century-Crofts, Inc., 1950. Pp. 165. $2.75.

Professors Mather and Roy first published *A Laboratory Manual of Physical and Historical Geology* in 1934. Roy at that time was in charge of laboratory work for Mather's big introductory geology course at Harvard University. Dr. Thiesmeyer was a graduate laboratory assistant. The present manual is a revision of the first part of that of 1934. A similar revision of the second part is scheduled for publication in the near future.

The proposed laboratory work is divided into thirteen units: six on minerals and rocks and seven on gradational processes and land forms as illustrated by topographic maps. The working time necessary to complete the entire set of exercises is estimated as approximately 40 hours for average students. Individual units will require anywhere from 2 to 4½ hours. It is expected that the semester's laboratory program will include, in addition, two or more afternoon field trips not provided for in the manual.

The exercises on minerals and rocks are based on rather elaborate sets of small study specimens, which are to be kept by each student in numbered pasteboard trays. Tray No. 1, for example, contains nine specimens illustrating Moh's scale of hardness. Tray No. 2 contains eleven specimens selected for various other physical properties. There are thirteen trays in all, with nearly one hundred and fifty specimens. The student retains the full set, together with the usual accessories—nail, magnet, streak plate, bottle of HCl, and pocket knife—until he has completed the first six units.

It is anticipated, further, that the instructor will have on hand a considerable quantity of "demonstration" material to supplement the student collections. The proposed contents of some two dozen drawers of such material are outlined in an appendix.

In working each unit the student records his observations on a series of forms, which are provided at the back of the manual.

The only materials required for the last seven units are topographic maps published by the United States Geological Survey and the Mississippi River Commission. From eight to twenty maps are suggested for each unit, of which not more than four or five will be issued to any one student. Different students

may use different maps in working the same unit. Four aerial photographs are provided in the manual. A standardized form is provided on which the student is to record his answers to questions on each assigned map or photograph. The introductory exercise on topographic maps also requires the preparation of a profile, for which graph paper is provided.

References to suitable background reading in most of the standard introductory textbooks are given at the beginning of each unit.

It is the procedure with rocks and minerals that constitutes the unique feature of this manual. The authors do not deny the difficulties of maintaining such large matched study sets for individual students—not to mention the demonstration material—but claim that these difficulties are more than compensated for by what the student gains through (1) training in orderliness, (2) opportunity for constant review, and (3) familiarity with a wide variety of forms of the same mineral or rock.

WILLIAM F. READ

Lawrence College

Silicate Melt Equilibria. By WILHELM EITEL. New Brunswick: Rutgers University Press, 1951. Pp. x + 159; figs. 200. $5.00.

This is a translation by J. G. Phillips and the late T. G. Madgwick (Department of Mines and Resources, Ottawa, Canada) of Dr. Eitel's *Die heterogenen Schmelzgleichgewichte silikatischer Mehrstoffsysteme* (Leipzig, 1943 and 1945), with revisions and additions by the author. The translators had the collaboration of the American Ceramic Society's Committee on the Physical Chemistry of the Silicates (R. B. Sosman, chairman, L. H. Adams, J. H. Koenig, F. H. Norton, E. F. Osborn, and N. W. Taylor). The author is a recognized authority in the field of silicate chemistry. He was formerly director of the Kaiser-Wilhelm Institute for Silicate Research and is now at the U.S. Bureau of Mines Electrotechnical Laboratory, Norris, Tennessee.

The translation leaves much to be desired from the standpoint of easy readability and comprehension. Words, phrases, or sentences which impart an obscure meaning or an awkward manner of expression are all too frequent. Examples of this are the following: "In order to control the specific case of the ideal alignment of chemical equilibria with silicates . . ." (1);[1] "Association reduces this correspondingly, namely analogous in amount to the degree of association" (15); ". . . obstinate non-equilibria . . ." (95); ". . . the incongruent field boundary UU′ merges incongruent throughout its whole length" (101); "In the mentioned pseudobinary system is observed that partly nephelite crystalline solutions form . . ." (135).

In general, the terminology is in conformity with standard American usage. Exception might be taken, however, to such phrases as "separate out" (36, etc.), "new-formation" (40, etc.), "isomorphously limited miscibility" (61), and "indifferent ceramic body" (154). Also, "reaction" is to be preferred to "conversion" (123, etc.), "diagram with isotherms" to "isothermal diagram" (147), and "inversion" to "transcrystallization" (191). Pluralization of "melt" and "melt-phase" is in most instances undesirable (46, 79, 123). Greater consistency in referring to certain features of phase diagrams would also be an improvement. Thus composition triangles are referred to variously as "ternary partial systems" (6), "three-phase triangles" (77), and "fields of concentration" (98). Primary fields are termed "fields of crystallization" (79), "fields of concentration" (120), and "saturation areas" (120).

In spite of the foregoing defects, largely attributable to difficulties of translation, the book is a welcome addition to the literature on phase equilibria. On the whole, the presentation of underlying principles has been adequate and orderly. The omission of one-component systems is not a serious one. Perhaps a more extended treatment of the phase rule and its modification for condensed systems could have been given. Greater clarity in the general discussion of equilibria, as in the case of monovariant equilibria in ternary systems (78) and polyphase equilibria in quaternary systems (234), would have been welcome. The discussions of the lever rule (20), the gravity center principle (73), stable and unstable phases (60), and isodimorphism (60) also suffer from lack of clarity. Although the quenching (static) method is not clearly outlined, its importance in ensuring the attainment of equilibrium is given well-deserved emphasis. Adequate stress has also been accorded to non-equilibrium phenomena. The importance in ceramics and metamorphic petrology of solid-state reactions would perhaps justify a more extended

[1] Numerals in parentheses refer to paragraph numbers in the text.

treatment of the latter. By implication, at least, the book expresses the widely held but questionable opinion that equilibrium is not attainable in the solid state (123, 167). Finally, a short presentation of order-disorder phenomena would have fitted in well with the discussion of polymorphous inversion.

Generous use has been made of schematic diagrams to illustrate the text. On the whole, these are excellent and adequately cover the field of silicate melt equilibria. Some readers may question whether the plotting of heat effects in figures 9, 10, 11, 16, and 17 aids in a better understanding of the diagrams. The use of single and double arrows for congruent (subtraction) and incongruent (reaction) curves, respectively, is commendable (97). So also is the addition of binary diagrams in figures 111–112, a feature which could with profit be extended (preferably with greater care than was shown in drawing these figures) to other ternary diagrams. Understanding of figures 108–112, 114–118, and 121–123 might be improved if solidus lines were more readily distinguishable from liquidus lines, as in figure 113. For many of the specific silicate systems pictured and discussed in the text, no reference is given other than the author's *Physikalische Chemie der Silikate* (2d ed.; Leipzig, 1941). Preferable for American readers would have been reference to the appropriate figure (which includes the original literature reference) in Hall and Insley's compilation, "Phase Diagrams for Ceramists" (Jour. Am. Ceram. Soc., vol. 30, no. 11, pt. II, pp. 1–152, 1947). There appears to be no advantage in discarding page numbers in favor of paragraph numbers, unless it is the frequent use of cross-reference in the text. Conformity with standard practice would still demand retention of page numbers. An index of systems cited and a subject index are helpful features of the book.

This reviewer is not convinced of the necessity for introducing the term "crystalline solution" in place of the widely used and equally adequate "solid solution." Unfortunately, too, the very impression of homogeneity which the new term is intended to emphasize is threatened by the use of such terminology as "crystalline aggregate" (45), "foreign substance" (44), "admixture" (59), and "mixed crystalline phase" (142). It is wrong to imply that, as cooling proceeds, the crystalline solution "becomes richer," or "is enriched," in the higher-melting component (46, 166, 191). It is also wrong to infer that crystalline solutions must be anisotropic (46, 50). The significance of "α" crystalline solutions in the case of the KCl-NaCl system is not apparent (62). It is not clear why two limiting crystalline solutions must occur in cases of partial miscibility (52); why such limiting solutions must unmix upon cooling (52); or why an upper critical mixing point is essential in cases of partial liquid miscibility (67). It is difficult to see how the "total instability" of a phase could complicate any phase diagram (60) or why the constant pressure needed to impose invariant equilibrium on four phases should be specifically "one atmosphere" (70).

The book is intended primarily for the ceramist, mineralogist, and petrographer. The systems which have been selected for discussion were carefully chosen with such readers in mind. The importance to petrology of the reaction-principle, resorption, and fractional crystallization, with the resultant possibilities of zoning (46, 110, 143), recurrent crystallization (101), the formation of ores and alkaline rocks (131), and reversal of zoning (158), is repeatedly emphasized. The application of such nonequilibrium phenomena to ceramic products (other than glasses and predominantly fused materials) is less obvious. Specific examples would have been welcome for resorption due to the pressure effect on shifting the eutectic (30) or on the transition from congruence to incongruence (31), phenomena alleged to be of great petrological importance. A few minor flaws, although with little bearing on the validity of the theoretical principles under discussion, should perhaps be noted: The treatment of Ca_2SiO_4-polymorphism is not up to date (36); $CaSiO_3$ is now known to invert at 1,125° C. (41); zircon is usually considered to melt incongruently (61); $FeSiO_3$ is ferrosilite, not gruenerite ($7FeO \cdot 8SiO_2 \cdot H_2O$) (191); and glaserite is probably a $(K,Na)_2SO_4$ crystalline solution rather than a distinct compound (223).

This is the only book in English which at all adequately presents the principles of phase equilibria with strong emphasis on silicate systems. If the present review appears unduly critical, it is because the reviewer anticipates that the book will enjoy a wide distribution. Despite its shortcomings, it helps to fill a long-felt need in the American literature on the physical chemistry of the silicates. It is indeed what the author intended it to be: a brief guide to the understanding of phase diagrams. Although it is not so clear and exacting as the author intended, the student will find it of incalculable aid in grasping the nec-

essary fundamental principles. He will then be the better able to study in greater detail, through reference to the original literature, those complex silicate systems briefly encountered in this book. It is to be hoped that the future editions which the book will undoubtedly enjoy will be freed of the defects which somewhat detract from the merits of the first edition.

WILFRID R. FOSTER

Champion Spark Plug Company, Detroit

Géologie stratigraphique. By MAURICE GIGNOUX. 4th ed. Paris: Masson & Cie, 1950. Pp. 735; figs. 155. Fr. 2,000.

Professor Gignoux's well-known handbook of stratigraphy has been revised extensively in this new edition. Essentially, the book is a compendium of European post-Proterozoic stratigraphy, in which an immense amount of literature and factual information has been compiled. The stratigraphy of Mediterranean countries, including northern Africa, is also included, but information on other parts of the world is sketchy and incomplete.

After 32 pages on general principles, in which the contrast between platform sedimentation and geosynclinal deposition is duly stressed, the author takes up briefly (17 pp.) the pre-Cambrian correlation and stratigraphy. The importance of the various systems for European geology is reflected in the length of the following chapters: Cambrian, 26 pages; Silurian (including the Ordovician of American usage), 36; Devonian, 55; Permo-Carboniferous, 117; Triassic, 52; Jurassic, 100; Cretaceous, 80; Paleogene, 92; Neogene, 51; and Quaternary, 66. As in the earlier editions, the descriptions are in regional order, new investigations and interpretations have been incorporated into the text, and references are given in footnotes. In a few places the author digresses to discuss special problems of facies and structural complications of correlation, or he inserts information on the meaning of words or the historical development of ideas and terms. Columnar sections are rarely given, but numerous new maps and diagrams illustrate the more important stratigraphic problems of contiguous areas. In the reviewer's opinion, their usefulness could be improved if scales were added to all. Many correlation diagrams, especially those in which several facies areas are represented, would be more illuminating if the reader could read off the distances within which one facies is replaced by another. This is particularly desirable where localities referred to are not familiar to most readers.

The author apparently has not had access to all the foreign literature of the last twelve years. His coverage of North America would have been facilitated by the numerous recent correlation charts published by the U.S. Geological Survey and the various stratigraphic committees of the National Research Council.

An eight-page index of geographic and formation names concludes the work. Many readers will wish there were another one for fossil names and general problems and terms. It might further increase the usefulness of this excellent treatise of European stratigraphy.

R. BALK

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Analyse des silicates. By ARNOLD LASSIEUR. ("Documents d'analyse chimique," Vol. 1.) Paris: Dunod, 1951. Pp. viii+184.

Many tests by the author (Lassieur) are the basis for his methods for one-decimal determination of the constituents of rocks, glasses, refractories, and related products and indicate to him the futility of more than a single evaporation for silica and single precipitations for the ammonia group, lime, and magnesia.

Preparation of the sample and qualitative tests for some of the rarer elements are considered in the twelve-page Introduction. Detailed discussion of the various analytical methods applicable to the main portion is followed by a chapter (8) which gives methods and procedures used by Lassieur. His practice of first igniting the sample on a Meker burner, removing the cake and grinding it in an agate mortar, and then mixing it with carbonates for the fusion seems unnecessary for rocks. Likewise, his procedure of separating the dried silica from the filter paper and igniting the two separately is unnecessary and undesirable.

Attention given to the determination of fluorine is commendable. Chapter 12 (20 pp.) is devoted to the subject, and a sketch of a distillation apparatus for use in the determination of fluorine after the method of Willard and Winters is included. The last two chapters deal with Lassieur's views on standardization of silicate analysis and precision of analytical results.

The book is not intended for refined rock or

mineral analysis, and it will be of greatest service in rapid technical analyses. Serious omissions are no mention of the colorimetric determination of manganese and no method for the direct determination of water or for the determination of strontia or of baria in the presence of strontia. There is a detailed Table of Contents, but lack of a subject index is a handicap.

SAMUEL S. GOLDICH

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Spectrochemical Analysis.[1] By L. H. AHRENS. Cambridge, Mass.: Addison-Wesley Press, 1950. Pp. xxiv+267+appendix of 72 tables of sensitive lines; figs. 52; pls. 5. $10.00.

Until fairly recent times, the chemical composition of a rock, mineral, or soil was thought to be known satisfactorily when an analysis had been made for fifteen or so of the major elements. Today the geologist, in requesting a "complete" analysis, is likely to ask for determination of twenty to forty additional, minor elements. This more thorough interest in the composition of geological materials is one of the most striking aspects of modern geochemistry.

Most of the data on the distribution of minor elements have been obtained through spectrochemical analysis, and spectrographic equipment is being installed in an increasing number of geological laboratories in this country. In this timely book, Ahrens has admirably summarized the extensive literature of the field and has organized it into a highly usable form.

The object of the book, as stated on the titlepage, is a discussion of "spectrochemical analysis arranged particularly for the D.C. arc analysis of minerals, rocks, and soils and applicable also to ceramic materials, refractories, slag, biological ash and powders in general." Description of various spectrographic equipment is held to a minimum, and emphasis is placed on techniques and principles. As the most comprehensive exposition of d.c.-arc methods, the book will appeal to a wide circle of analysts, teachers, and students.

There is first a logical division into two parts; part 1, "General Principles," in ten chapters; and part 2, "The Elements," in thirteen chapters. Part 1 covers such topics as origin and interpretation of spectra, physical features of the d.c -arc, qualitative analysis, selective volatilization, principles of quantitative analysis with and without internal standardization, effect of change of composition on line intensity, and spectroscopic buffers. There is a well-balanced comparison of the advantages and disadvantages of cathode layer versus anode mode of excitation. The entire discussion of part 1 is a most encouraging attempt to reduce the many-sided art of d.c.-arc analysis to a state of science.

Harvey's practical definition of detection limits (*Method of Semi-quantitative Spectrographic Analysis* [Glendale, Calif.: Applied Res. Lab., 1947], p. 13) is missing from the discussion of this subject (p. 60). A more detailed comparison of the characteristics of photographic emulsions used in Europe and America (pp. 126–127) would lead to a clearer understanding by American spectrographers of Ilford, Perutz, and other emulsions mentioned in European literature.

Part 2 covers the spectrochemistry of fifty-seven minor elements plus nine major elements. "Spectrochemistry" is conceived by Ahrens as a "term which embraces all those properties of an element pertinent to its analysis; for example, ease of excitation, volatilization rate, complexity of spectrum, and other characteristics." Useful geochemical information on the occurrence of the various elements is also given. Both general procedures for simultaneously determining a large number of elements and specialized procedures for individual elements are reviewed in thirteen well-organized chapters. Throughout the book, hitherto unpublished data obtained by Ahrens and his co-workers at M.I.T. have been added to bolster the available information.

There is an appendix of seventy-two tables, listing two to four sensitive lines of the elements, together with other lines lying within ± 0.5 Å, as given in the M.I.T. wave-length tables. Some of the errors that have been found with regard to sensitive lines and their neighbors are mentioned in part 2 of the book, but unfortunately they remain uncorrected in the tables. If these tables are to be issued separately, they should be accompanied by a list of all erroneous, doubtful, or missing entries.

The printing and binding are of good quality, and the Index is well organized.

K. J. MURATA

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[1] Publication of review authorized by the Director, U.S. Geological Survey.

General Proceedings, Pt. 1: *Report of the 18th Session, International Geological Congress, Great Britain, 1948*. London, 1950. Pp. 255.

Apart from the customary records of organization, committees, financial statements, and welcoming addresses, this volume contains (pp. 42–118) a list of participants and members with addresses. Two items in the general secretary's report are important: Russian will henceforth be an official congress language; and it was voted, after lengthy discussion, to postpone the formation of an international union of geology. However, the Bureau of the International Congress is prepared to give to UNESCO such information on geological matters "as its judgment allows it to do."

Eight sheets of the new second edition of the *Geological Map of Europe* (London, Berlin, Warsaw, Marseilles, the Alps, the Carpathians) are published, and several others are presumably ready for distribution now. They may be obtained from the Hessisches Landesamt für Bodenforschung, Wiesbaden, Parkstrasse 38, Germany—U.S. Zone (see p. 188).

It appears (pp. 209–210) that at least four or five sheets are now available of a new geological map of Africa, on a scale of 1:5 million, in nine sheets, but the address where they may be bought is not given. The reviewer assumes that the Wiesbaden office will furnish information on this map.

A progress report of the Commission on the Distribution of the Gondwana (Karroo) System (pp. 193–206) contains summaries of new research, classifications, and correlations of these rocks from India, Africa, Belgian Congo, Argentina, Bolivia, Brazil, Southern Rhodesia, the Union of South Africa, and Madagascar, as well as a statement by Curt Teichert on climates of Australia during the Carboniferous, Permian, and Triassic periods.

A group of geologists under the chairmanship of Dr. Louis L. Ray (U.S. Geological Survey) is exploring means of organizing a section of geomorphology at the next session of the International Geological Congress at Algiers, and it is hoped that an international physiographical map may be prepared in due time. It is proposed that a Temporary Commission on Meteorites be converted into a permanent commission of the congress, under the chairmanship of Walter Wahl (Helsinki). United States members are J. P. Marble, F. H. Pough, W. Foshag, and E. Perry.

The last forty pages of the volume are addresses by O. T. Jones and Sir E. B. Bailey on the structural geology of England and Wales and of Scotland, respectively, serving as general outlines for the participants of excursions that followed the sessions of the congress in London.

R. Balk

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Metasomatic Processes in Metamorphism, Pt. 3: *Proceedings of Section B, Report of the 18th Session, International Geological Congress, Great Britain, 1948*. London, 1950. Pp. 131.

This volume contains thirteen papers and abstracts of five additional ones that were read and discussed during the three sessions of the Section on Metasomatic Processes in Metamorphism. The authors are Eskola ("Nature of Metasomatism in the Processes of Granitization"), Magnusson ("Origin of the Sörmland Gneisses, Sweden"), D. L. Reynolds ("Transformation of Caledonian Granodiorite to Tertiary Granophyre on Slieve Gullion, Ireland"), Backlund ("Homogenization and Geochemical Discontinuities in Granitic Areas"), Wegmann ("Metasomatic Transformations and Tectonic Analysis," in French), Glangeaud ("Thermodynamics of Petrogenesis at Depth," in French), Korzhinsky ("Differential Mobility of Components and Metasomatic Zoning in Metamorphism," in both English and Russian), Bianchi and Dal Piaz ("Selective Metamorphism and Metasomatic Processes at the Contact of the Adamello Massif," in Italian), Von Eckermann ("Process of Nephelinization" and "Genesis of the Alnö Alkaline Rocks"), Zavaritsky ("Metasomatism and Metamorphism in the Pyrite Deposits of the Urals," in both English and Russian), Ian Campbell ("Magnesium Metasomatism in Dolomite, Lucerne Valley, California"), and Alderman ("Genesis of Sillimanite and Kyanite Rocks by Alumina Metasomatism"). The concluding five pages are abstracts of papers by Nel, Roubault, Bruet, Marinos, and Sorotchinsky.

It is difficult to do justice to the large amount of investigation, effort, and interpretation brought together in the pages of this volume. That different investigators have different ideas about the origin of granitic and metamorphic rocks has been known for some time. Judging from the discussion remarks, this disagreement continues, and in the same spirit of mutual es-

teem that was evident at the Ottawa meeting of the Geological Society of America in 1947. It is encouraging that there remains an appreciable area of agreement as well, which commonly grows as an author limits himself to the discussion of one particular area or subject and adduces detailed facts in support. Thus the beautiful microscopic and chemical investigation of Doris L. Reynolds appears to have convinced her listeners that, under the effect of heat emitted by a Tertiary basaltic magma, an older granodiorite can be converted into an appreciably more potassic and siliceous rock having the microscopic features typical of granophyre. Von Eckermann's painstaking study of the alkaline rocks of the Alnö district shows that for this particular mass an apparently erroneous interpretation had been given because the field mapping was inaccurate. Masses of "limestone," formerly thought to be xenoliths and evidence for generation of an alkaline magma by limestone syntexis, turn out to be dikes, resembling strikingly the cone sheets of the Scottish intrusive centers. The investigation is most comprehensive, and the evidence seems very satisfactory that pre-Cambrian migmatites have been enriched in carbonate "by an intruding carbonatic magmatic liquid" (p. 90). Enhanced temperature and pressure are held responsible for intensive shattering of the wall rocks, and the changes produced in the quartz and feldspar of the original wall rocks are portrayed in remarkable detail. Feldspar, for example, has first been hydrated to montmorillonite, and this was converted to nepheline, which appears to be so high in potash that the author regards the primary alkaline intrusion as "excessively potassic and only very slightly sodic" (p. 92). No less than nine concentrically arranged, vertical cylindric zones of alteration stages are mapped. In the discussion, Shand reiterated his belief that many alkaline intrusions are satisfactorily explained by desilication of magmas by limestones, and it is gratifying that Von Eckermann replied that he believes that this is "a fact in several areas, but not at Alnö" (p. 100). To the reviewer this seems a very commendable attitude. Until we have chemical and microscopic information from thousands of hitherto unmapped or unseen outcrops and until we have done much more careful mapping of rocks, it seems wise to consider more than one combination of processes and mechanisms that may be capable of producing one particular end-result. We may have reason to prefer one explanation for the genesis of one particular mass or complex of rocks; it is very heartening to find as competent a petrologist as Von Eckermann willing to concede that other alkaline masses may have formed through a different sequence of conditions and events.

Disagreement is apparent in the discussion when authors have made generalizations or were unable for one reason or another to adduce evidence for each and every link in the chain of their reasoning. To Eskola there is satisfactory evidence that in Fennoscandia granitic rocks have formed through ordinary magmatic processes or through metasomatic replacement. To him the presence of H_2O in virtually every chemical rock analysis is a strong argument that water has been present at practically all reactions between minerals, no matter how small its amount. He therefore minimizes the effect and geological importance of diffusions in entirely dry materials. But when he says: "My thesis is therefore that all granites are magmatic" (p. 10), without explicit qualification, it is understandable that disagreement results; for, as Eskola takes pains to point out elsewhere, the connection between an actual magma and the pore liquid that may be capable of making a granitic rock may be sufficiently circuitous to render exact proof in some regions difficult, if not impossible. On the other hand, it is somewhat surprising that Arthur Holmes, in the ensuing discussion, claims that he has completely lost faith in the existence of a granite magma, when he does not criticize any particular statement or observation made by Eskola.

Magnusson and Backlund have pictured in remarkable detail the various stages by which the early pre-Cambrian sedimentary and volcanic rocks of central Sweden have been converted into veined and mixed gneisses. Magnesium enrichment is followed in the Sörmland district by feldspathization and growth of pegmatitic veins, which, in Magnusson's opinion, were generated by higher temperatures when the terrane was depressed, so that metamorphic differentiation and palingenesis began to operate.

Backlund's paper outlines evolutionary stages of a large, coarsely porphyritic gneiss complex and of another medium and even-grained gneiss complex. The isoclinically folded structure of the original sedimentary rocks is believed to have exerted considerable influence in guiding zones of maximum transfer of material; feldspar phenocrysts are thought to have devel-

oped at relatively shallow levels; and, where carbonaceous sediments were involved, the attendant reduction has produced gray instead of the ordinary pink or red gneisses.

These few selected items may give some indication of the variety of problems discussed in the volume and the various opinions expressed by participants in the meetings.

R. BALK

University of Chicago

Oil-Field Exploration and Development, Vol. 1: *Oil-Field Principles;* Vol. 2: *Oil-Field Practice*. By A. BEEBY-THOMPSON. 2d ed. London: Technical Press, Ltd. Pp. 1168; figs. 270; tables 50; maps 8; appendixes 11. $20.00.

To a young geologist who before the first World War found himself confronted with responsibility for assessing the validity of surficial evidences of petroleum resources in remote parts of the world, the discovery of the early writings of A. Beeby-Thompson seemed rare good fortune. Here was an engineer who had observed keenly and written comprehensively of the occurrence of oil and of the nature of oil fields, all over the earth. Not the least merit of these remarkable studies of petroleum—*The Oil Fields of Russia, Petroleum Mining*, and *Oil-Field Development*—is that they were widely current and were available in remote places almost as soon as the search for petroleum over the earth got under way. With the exception of the contemporary work of a British colleague—Sir Boverton Redwood's monumental, three-volume compendium, *A Treatise on Petroleum*, the fourth edition of which appeared in 1922—there was at the time nothing else like these pioneer reference works on the occurrence of petroleum and the techniques of the petroleum industry. Americans, despite their leadership in the effort to find and produce oil, seem to have left it pretty much to the British to compile handbooks of the world's petroleum industry. Even today the most imposing handbook of petroleum is *The Science of Petroleum*, in four volumes, published by Oxford University Press, London.

As a young man, A. Beeby-Thompson, the author of *Oil-Field Exploration and Development*, identified himself with the petroleum industry of Russia. This experience—unusual among English-speaking engineers—served as background to his subsequent studies of petroleum elsewhere over the world. It was the first step along a path which the author has followed assiduously throughout his adult life and which has led him to a comprehensive knowledge of the earth's petroleum resources and the principal oil fields through which society exploits these resources.

When the first edition of *Oil-Field Development* was exhausted in 1922, the author attempted to revise the original text and publish the revision as a new edition. Very soon, however, he abandoned this attempt. "In consequence of the startling rapidity of developments in all sections of the oil industry," he found the task impossible. So also in the case of the present second edition of *Oil-Field Exploration and Development*, author and publishers "have reluctantly agreed" to reissue the old volumes with the addition of appendixes that would bring essential data up to date.

What we now have in the second edition, therefore, is a reprint of a valuable reference book on petroleum which has long been obtainable only with difficulty, together with an informative—if brief—account of the discovery and development of oil fields, the evolution of thought on the origin and occurrence of petroleum, and the improvement of techniques for finding, producing, transporting, and refining oil, over the last quarter-century. Despite the fact that the author came reluctantly to the decision to publish his second edition in this form, the result is fortunate, in that it makes more widely available a comprehensive and accurate portrayal of the petroleum industry, world wide, twenty-five years ago, together with some of the best descriptions on record of little-known occurrences of petroleum.

Volume 1, *Oil-Field Principles*, comprises eleven chapters, aggregating 546 pages, together with the four appendixes, some 25 pages, which bring the essential data down to date.

Chapter 1 discusses the general distribution of petroleum, and it is gratifying to find the discussion organized around the character and position of the geosynclines of the earth. Not all of us visualized clearly so long ago the relationship between geosynclines and the occurrence of petroleum.

Chapter 2 is entitled "Origin of Oil"; chapter 3, "Formation of Oil Fields"; chapter 4, "Characteristics of Oil Measures"; and chapter 5, "Oil-Field Structures." These chapters cover the origin, migration, and accumulation of oil, the

stratigraphy of oil-bearing rocks, and the structure of oil fields. The author is puzzled (as who of us was not at that time) at the "mysterious" conditions of oil accumulation in limestone reservoirs, but he concludes that sands and "arenaceous oil-bearing strata" are more important than limestones as reservoir rocks. Chapter 4 contains several excellent photographs of oil sands, but it will hardly be necessary to say that nowhere in the discussion of reservoir rocks is there any mention of reefs or bioherms, so recently have reefal occurrences of oil come to be recognized.

Chapter 6, "Oil Indications and Their Significance," and chapter 7, "Phenomena Associated with the Development of Oil Fields," are the two longest chapters in volume 1, a circumstance which reflects, perhaps, the author's predominant interest in the fields covered by them. In chapter 6, the discussion of mud volcanoes is notable.

Chapters 8, 9, and 10, comprising approximately one-third the volume, are devoted to the geology of oil fields over the world. In these chapters, also, the geographic distribution of oil fields and of occurrences of oil is discussed, and all these are described clearly, with remarkable detail.

Chapter 11, "The Properties and Treatment of Petroleum," includes a discussion of refining, although the other functions—producing and transportation—are reserved for volume 2, *Oil-Field Practice*

Volume 2 opens with an introductory chapter touching on the history of the industry, legislation, leasing practices, and appraisal of oil properties. The following chapter deals with drilling methods, and, as might be anticipated, considering the time at which the chapter was written, more space is devoted to cable-tool and pole-tool processes than to rotary drilling. Subsidiary operations, such as fishing, testing, shooting, and controlling gas pressures in oil wells, are discussed in the next chapter, and then the "lining of oil wells" is taken up. This quaint phrase is used only in the chapter title, and the discussion immediately adopts and adheres to the term "casing," so much more familiar to American ears. Chapter 16 is devoted to oil-field waters, and chapter 17, "The Recovery of Petroleum," discusses methods of producing oil from wells and incident problems. This long chapter is much concerned with pumping, bailing, swabbing, and air-lift—methods for "reviving drooping wells." These methods were widely used in early days, in contrast to modern emphasis on flowing methods of production. There follows a chapter on oil-field equipment and special problems, such as oil-field fires. The next chapter covers storage and transportation of oil, and chapter 20, the final chapter of the book, is a brief review of natural gas, casing-head gasoline, and carbon black. The book ends with an appendix, made up of "Useful Tables and Data."

The special appendixes to volume 1, three in number, describe clearly and emphasize the significance of the improvements and changes in techniques which have been invented, developed, and put into practice by the oil-producing industry since 1924. The amazing progress in perfecting methods for exploration is graphically portrayed, and the new methods are briefly described. Oil-field discoveries and developments since 1925 are reviewed in competent fashion, country by country. The section dealing with the countries of the Middle East is admirable.

The five special appendixes to volume 2 cover progress over the last quarter-century in (1) "Refining," (2) "Oil-Field Controls," (3) "Drilling Techniques and Logging of Wells," (4) "Recovery of Oil," and (5) "Natural Gas and Gasoline."

Despite obviously painstaking editorship, there are occasional small errors, none of which is serious enough to merit notice here. Altogether, the petroleum industry is fortunate to have preserved for it in the form of a new edition this valuable early reference work.

WALLACE E. PRATT

Carlsbad, New Mexico

Petroleum Geology. By KENNETH E. LANDES. New York: John Wiley & Sons, Inc., 1951, Pp. xi+660; figs. 222. $10.00

Professor Landes has brought together a wealth of information in this new textbook. Progress in petroleum geology during the last two decades has been so rapid that it is a major task for anyone to assemble the essential data into a single volume. The author has succeeded well in accomplishing this task by dividing his text into three main portions. The first part concerns the techniques of the petroleum geologist, the second part discusses the geologic occurrence of petroleum, and the third part describes

the known distribution of oil and gas and touches upon future supplies.

The techniques of the petroleum geologist are covered in the first ninety-seven pages of the book, immediately following an introductory portion on the profession of petroleum geology. Oil-finding techniques are divided into surface methods, subsurface geological methods, and geophysical methods. Subsurface samples, electric logs, and radioactivity logs are described and discussed, and their applications to subsurface mapping are developed. This section of the book has been purposely kept rather brief by the author, who rightly holds that the only way to learn about oil-finding techniques is through experience. Nevertheless, the chapter on techniques introduces the student to the major principles which underlie exploration.

A short chapter on oil-field exploitation, including completion practices, reservoir characteristics, estimates of reserves, and oil property valuation, completes the first part of the volume.

The second part of the textbook, covering about two hundred pages, includes the properties of oil and gas, their origin and evolution, migration, and accumulation. The theories of origin are well summarized, and the author here and there presents his own conclusions rather than leave the student lost in a maze of controversial mechanisms. The treatment of reservoirs (traps) in chapter 8 is outstanding. A relatively simple classification is followed, based on a modification of Wilson's 1934 classification, which includes structural traps, varying permeability traps, and combination traps. Each type of trap is illustrated by one or more examples, well illustrated with maps and sections. This chapter not only provides the student with an excellent introduction to the many kinds of traps in which oil is found but is of considerable value to the practicing oil geologist for its excellent review of the subject.

The third and last part of the book is devoted to present and future oil supplies. The present known oil distribution is treated by states from east to west. Although the discussion is comprehensive, the geographic boundaries on the maps partly obscure the broader basinal relations in some areas. The basis of subdivision is appropriately one of convenience, however, and the arrangement does not detract from the presentation. Future oil supplies are considered in terms of deeper reserves in presently drilled areas and new reserves in presently untested areas.

The reviewer believes that Landes has produced an outstanding textbook, well organized, and written in a very readable style. The illustrations were all drawn especially for the text, and they add a unity lacking in books which directly reproduce original illustrations. The volume should find wide use as a textbook, and it is recommended to the professional worker as an up-to-date review of the subject.

W. C. KRUMBEIN

Northwestern University

"Report of the Committee on a Treatise on Marine Ecology and Paleoecology, 1949–1950." Edited by HARRY S. LADD, chairman. Washington: Division of Geology and Geography, National Research Council, 1950. Pp. 59. $1.00. Mimeographed.

This report, like its predecessors of the past few years, contains chapters devoted to "Current Activities," "Recent Publications," and "Completed Units of the Treatise."

The forthcoming "Treatise on Marine Ecology and Paleoecology" is expected to be in press by 1952. It will be published in two volumes, which will be priced at not more than twenty dollars. The several completed chapters which have appeared in previous reports will give those who are interested a general idea of the type of material to be presented in the "Treatise."

The "Current Activities" section contains remarks on projects planned or in progress throughout the country and in the Pacific. These abstracts call attention to the wide variety of work in progress: from detailed studies of pre-Cambrian algal structures to an investigation of the modern tidal-flat environment and its sediments.

The completed unit of the "Treatise" in this report is "Annotated Bibliography of the Ecology of Marine Bacteria," by C. E. ZoBell.

Included is a note entitled "Strontium Biogeochemistry, Ecosystems, and Paleoecologic Tools," by H. T. Odum, which presents some interesting ideas on the geo-economy of strontium and the use of the Sr-Ca ratio as an environmental index.

R. N. GINSBURG

University of Miami

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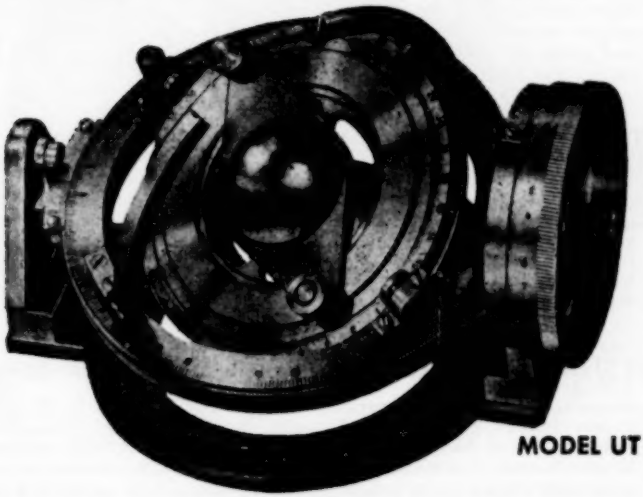

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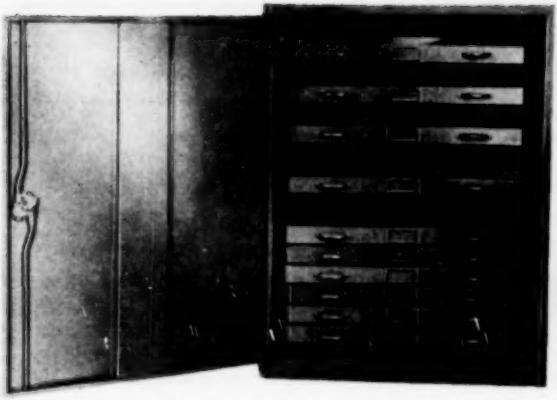

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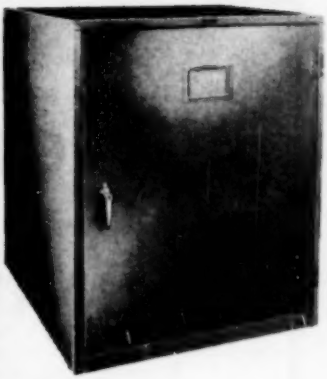

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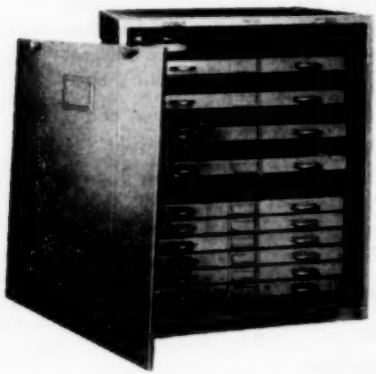

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